Volume 30 JUNE, 1960 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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FIGS. 1–11, JUNE, 1960

THE MAM TOR SANDSTONES: A "TURBIDITE" FACIES OF THE NAMURIAN DELTAS OF DERBYSHIRE, ENGLAND[1]

J. R. L. ALLEN
University of Reading, England

ABSTRACT

The Kinderscoutian Mam Tor Sandstones (400 ft thick) at Mam Tor, Derbyshire are formed by a monotonously repeated cyclothem (sandstone-shale group) in which grain size diminishes upwards from the base. Shales, mudstones, siltstones, sandstones (laminated and non-laminated), and shale conglomerates and breccias are the chief rock types present. The sandstones are ill-sorted, bearing detrital clay matrices and some plant debris. Marine pelecypods occur in the shales. The sandstone-shale groups are widely persistent laterally and on their sharp soles bear groove casts, flute casts, load casts, sludge casts, and trail casts. Convolute bedding, corrugated bedding, crumpled bedding, and slump-ball structures are often found.

The Mam Tor Sandstones, derived from sources which included metasedimentary and granitic rocks, were probably deposited in deep quiet waters by currents which at first flowed along roughly east-west lines and later, more importantly, flowed southwards. In the Mid-Pennines the Mam Tor Sandstones pass into coarse sandstones bearing coals. These, of the same age as the Mam Tor rocks, were deposited also by mainly southerly currents, apparently in the shallow water environments of a delta complex. The Mam Tor Sandstones are suggested to be the deposits of turbidity currents which may have originated in slumps of the shallower delta sediments co-existing higher on the submarine slopes.

INTRODUCTION

The upland moors of north Derbyshire, England, familiarly known as the Peak District, widely expose the rocks of the Upper Carboniferous Millstone Grit (Namurian). The succession (2700 ft) has been described recently by Jackson (1927), Fearnsides and others (1932), Bromehead and others (1933), Hudson and Cotton (1943, 1945), and Eden and others (1957).

The Namurian begins with the Edale Shales (750 ft) resting with local unconformity on the Visean (Lower Carboniferous) shales and limestones. The Edale Shales bear goniatites representative of the Pendleian, Arnsbergian, Sabdenian and, in part, Kinderscoutian stages of the British Namurian classification. The upward succession of the Kinderscoutian continues with the Mam Tor Sandstones (400 ft), the Shale Grit (450 ft) and the Grindslow Shales (300 ft). The Kinderscout Grit (400 ft) ends the Kinderscoutian in the central Peak District. The succeeding Middle Grit Group (Marsdenian) and Rough Rock Group (Yeadonian) crop out to the east and west and underlie the thick Coal Measures completing the Upper Carboniferous.

[1] Manuscript received August 7, 1959.

The Millstone Grit of Derbyshire and the Pennine Chain to the north has long been regarded as a complex which origniated in marine deltas. This paper, part of a wider study, describes the Mam Tor Sandstones at the type locality of Mam Tor, Derbyshire. Evidence is presented suggesting that the Mam Tor Sandstones were deposited by turbidity currents during one phase in the growth of the Namurian deltas. These rocks are believed to be the first from the Upper Carboniferous of Northern England for which such a claim has been made.

SUCCESSION

The east face of Mam Tor, sited between the Vales of Edale and Hope 15 miles west of Sheffield, is scarred by a large landslip. The highest Edale Shales and some 350 ft of the Mam Tor Sandstones are excellently exposed on the steep cliff thus revealed. Almost all the beds are accessible. The Mam Tor Sandstones begin at the first sandstone seen above shales bearing limestone concretions. Throughout their succession a lithological group or cyclothem (Wanless and Weller, 1932, p. 1003) is monotonously repeated; it consists of sandstones at the base grading upwards through siltstones into

FIG. 1.—Sandstones and shales in the upper part of the Mam Tor Sandstones, Mam Tor. Sandstone beds in the foreground are about 3 ft thick and extend laterally for about 300 ft.

shales. *Sandstone-shale group* is a convenient title.

The general features of the higher Mam Tor Sandstones are shown in figure 1. The shales of the groups underlie steep slopes of talus while the sandstones give rise to deeply undercut ribs. Grading and sole markings can be examined with ease. The groups range from 3 in to 8 ft in thickness, and even the thinnest are remarkably persistent laterally. They emerge from beneath sub-soil and turf and can be traced across the face for as much as 800 ft without notably changing their thickness or lithologic composition. None have been seen to wedge out. A plot of the cumulative thickness of 74 sandstone-shale groups gave a straight line on log probability paper (compare Bokman, 1953, p. 155). Sharp bedding planes, or soles, lie beneath the sandstones and demarcate the groups from each other. The soles are sometimes smooth and undulose but more commonly bear markings of several kinds.

Sandstones increase in abundance upwards in the Mam Tor Sandstones. Concomitantly, the shales become sandier and are associated more frequently with mudstones. Many short sequences can be made out in which the sandstone-shale groups are almost uniform in thickness; in some the groups are thin (about 2 ft), in others thick (about 5 ft). A few sequences bear groups of the maximum thickness range. A detailed succession is given below.

0 to 100 ft—About 30 groups from 3 in to 7 ft thick are present. Sandstones in the groups aggregate from 1 in–4 ft. An estimate of the sandstone-shale ratio of the sequence gave 0.83. The shales bear poor specimens of *Posidoniella sp.* and *Pterinopecten sp.*

100 to 114 ft—The beds here are black shales and calcareous mudstones bearing poorly preserved pelecypods but no goniatites. There are thin layers of siltstone, calcite cone-in-cone, and calcareous concretions.

114 to 149 ft—Seventeen sandstone-shale groups follow and range from 6 in–7 ft thick, seven exceeding 3 ft. The sandstone-shale ratio is 0.83, and the sandstones of the

groups range to 5 ft. The shales occasionally yielded pelecypods.

149 to 163 ft—Two groups are present, easily picked out on the Mam Tor face. The lower is 8 ft thick, bearing sandstones aggregating 6 ft. The upper is 6 ft thick and bears 5 ft of sandstones. The sandstone-shale ratio estimated was 0.78.

163 to 184 ft—Here there are 5 groups 2 to 5 ft thick. Each carries sandstones less than 2 ft thick. The sandstone-shale ratio was estimated at 0.30.

184 to 198 ft—Nine groups 1 to 2 ft thick follow. The sandstones in the groups rarely exceed 1 ft, and the sandstone-shale ratio estimated was 0.75.

198 to 219 ft—Five sandstone-shale groups are present, one of 9 in, the remainder of 3 to 8 ft. The sandstones in each group never aggregate more than 5 ft. The sandstone-shale ratio of 0.93 was estimated.

219 to 229 ft—Nine groups follow and range from 3 in to 2½ ft thick. Never more than 6 inches in each group is of sandstone, an estimate of the sandstone-shale ratio giving 0.40. The shales bear some pelecypods.

229 to 246 ft—Four groups 2 ft 3 in to 7 ft thick are present. Each group carries sandstones less than 2 ft thick. The sandstone-shale ratio was estimated at 0.40.

246 to 266 ft—About 15 sandstone-shale groups follow and range from 6 in to 3 ft thick. Sandstones in each group never exceed 2 ft, and an estimate of the sandstone-shale ratio gave 1.0.

266 to about 350 ft—These beds reach to the highest point on the Mam Tor face and to within 50 ft of the top of the Mam Tor Sandstones. About 50 sandstone-shale groups were counted although not all proved accessible. Most are less than 2 ft thick. A few of about 5 ft are grouped into several short sequences. Sandstones are predominant, and the sandstone-shale ratio was estimated at 3.0. The shales are sandy and associated with sandy mudstones. At Back Tor, 1 mile northeast of Mam Tor, these beds pass up slowly into the coarser grained and thicker sandstones beginning the Shale Grit.

The succession of the Shale Grit resembles the Mam Tor Sandstones in many respects. Thin to thick (1–20 ft), coarse, massive sandstones are interbedded with and become finer as they pass up into much thinner siltstones, sandy mudstones, and sandy shales. The sandstones are persistent laterally but often thicken and thin irregularly, a few wedging out. They rest sharply on the siltstones or shales beneath and commonly bear sole markings. Load casts, groove casts, and flute casts were found.

The rock types of the Mam Tor Sandstones, their manner of arrangement, and the depositional and deformational structures which they show are described below.

LITHOLOGY

Shales and Mudstones

Shales are abundant, a common variety being soft, unlaminated, papery, black, carbonaceous, and uniform in grain size. These pass into uniformly graded, hard platy, unlaminated, black shales. Both types often yielded pelecypods. Shales in the lower part of the Mam Tor Sandstones sometimes bear small discoidal limestone concretions, the "bullions" of many British writers. Thin bands of dark gray, calcareous, sideritic mudstones are also present. The mudstones break with a conchoidal fracture and bear thin bands of calcite cone-in-cone.

Dark gray to pale brown, platy, silty shales grading into sandy mudstones are most plentiful among the higher beds at Mam Tor. Carbonates and carbonaceous matter are always rare.

Laminated Siltstones

Gray laminated rocks of silt grade are common and link the shales with the sandstones. A laminated siltstone coarsening downwards into laminated sandstone is shown in figure 2. Ripple-drift bedding (Sorby, 1908, p. 181) is typical of the laminated siltstones. It consists of tabular or lensing slightly inclined layers reaching 5 cm in thickness and bearing low-angle cross stratification. Many bedding planes reveal parallel or linguoid transverse current ripple-marks. These are expressive of the ripple-drift bedding seen normal to the general stratification.

The individual laminae of the siltstones are poorly sorted and rarely exceed 1 mm in thickness. Some laminae consist chiefly of quartz with a little detrital clay mineral and clastic mica. Other laminae, darker in col-

FIG. 2.—Vertical section through a graded bed of laminated sandstone and laminated siltstone. Small, striated, groove casts are present on the lower surface (not shown). Reading Univ. Dept. Geol. Mus. no. 13003.

our, are rich in detrital aggregates of microcrystalline siderite. Small fragments of carbonised wood appear in most thin slices. Many bedding planes are strewn with plant debris locally pyritised after coalification.

Laminated Sandstones

The laminated sandstones are abundant, gray in colour, and of very fine to medium grain. Their laminae are typically thick (1–5 mm), regular, parallel, and widely persistent laterally in contrast to the siltstone laminae. The finer grained sandstones, transitional to the siltstones, are less regularly stratified and sometimes show ripple-drift bedding, transverse current ripple-marks appearing on the bedding planes.

The laminae of many sandstones range widely in composition and sorting. Some of the laminae, normally moderately to well sorted, consist chiefly of quartz and a little feldspar, rock fragment, mica, and clay mineral. The usually poorly-sorted interbedded laminae are replete with siderite aggregates and sideritic mudstone grains. By contrast, some of the sandsones are rich throughout in quartz, others in siderite.

The range in modal composition of the laminated sandstones is shown in figure 3. Quartz (13.1 to 74.3 percent) appears as angular to subangular grains chiefly of simple type. Cryptocrystalline to microcrystalline sericitic clay minerals comprise up to 20.9 percent and form the detrital matrix of many sandstones. The unstable components (6.0 to 86.8 percent) include feldspar, rock fragments, mica, siderite aggregates, and wood.

The feldspars (0.3 to 2.0 percent) are chiefly subrounded grains of orthoclase, albite, and microcline. The microcrystalline siderite aggregates and subordinate sideritic mudstone grains (2.1 to 85.2 percent together) are usually squeezed between the contiguous particles. The rock fragments (microcrystalline silica) and the micas (muscovite), the latter the more abundant of the two, at the most total 4.4 percent. Wood reaches a maximum of 2.9 percent and in many beds appears as large fragments of leaves and stems. Some of the laminated sandstones bear a little calcite cement, but typically the grains are bonded by the detrital clay and the secondary enlargments of the quartz.

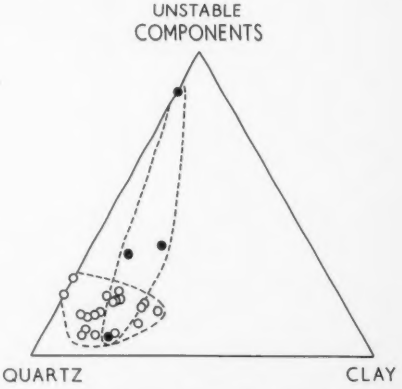

FIG. 3.—Diagram showing the amounts of quartz, clay, and unstable components (feldspar, rock fragments, micas, siderite aggregates, mudstones, and wood) in non-laminated sandstones (open circles) and laminated sandstones (solid circles), Mam Tor Sandstones, Mam Tor. The analytical error (Chayes, 1956, p. 56) on the major components is less than 1.5 percent.

Non-laminated Sandstones

Non-laminated sandstones are very abundant at Mam Tor, giving rise to thick massive units. The rocks are gray to brown in colour and range from the medium sand to granule grades. Those of finest grain are transitional to the laminated sandstones and often bear discontinuous laminae. Layers of shale pebbles in others give rise to rough impersistent partings.

The non-laminated sandstones are less varied in composition than the laminated type although formed of the same constituents (fig. 3). However, the degree of sorting varies much more greatly. The sandstones bearing clay are usually very poorly sorted. They carry little or no calcite or quartz cement and resemble in texture the graywackes of Pettijohn (1957, p. 302). A few of the non-laminated sandstones are rich in calcite cement, clay being absent or of minor importance. These sandstones are well sorted and therefore similar to Pettijohn's (1957, p. 298) orthoquartzites. They are found chiefly among the higher beds at Mam Tor.

Angular to subrounded grains of quartz, often secondarily enlarged, range from 55.6 to 81.2 percent. The larger grains and the granules are mainly of compound type and occasional schistose fragments (sub-parallel micas) were also measured. Fresh grains of untwinned orthoclase, normally twinned albite, and microcline are the principal feldspars (1.0 to 11.9 percent). Locally these grains are replaced by kaolinite or jaggedly etched by calcite. The rock fragments (microcrystalline silica) and the more abundant micas together make up 1.2 to 6.5 percent. Flakes of muscovite reaching 5 mm in diameter are common. Grains of microcrystalline siderite, sideritic mudstone, and mudstone comprise as much as 10.0 percent. As much as 1.3 percent of wood occurs in the thin slices. Large fragments (20 cm in length) of plant leaves and stems (some *Calamites*) abound in several of the non-laminated sandstone beds. Calcite cement is normally absent or low but in one "orthoquartzitic" sandstone reached 42.6 percent.

Shale Conglomerates and Breccias

The conglomerates are non-persistent layers of crowded shale pebbles set in the non-laminated or laminated sandstones. The pebbles are discoidal and up to 5 cm in diameter. Many are little more than irregular wafers of shale, perhaps the result of compaction from an almost "soupy" state.

Less frequent but more striking are breccias of large shale fragments set in the coarser non-laminated sandstones. A fine breccia (fig. 4) approximately 155 ft above the base of the Mam Tor Sandstones bears angular to well-rounded pieces of shale and silty shale. The fragments average approximately 20 cm in length, the largest being 75 cm long. Elsewhere in this bed, and in others too, the chunks range to 1.25 m. Most of the pieces of shale are flat-lying, but the grading in the siltier fragments shows that some are inverted with respect to the breccia. The laminae of the silty shales are sometimes contorted, pointing to the plastic state of the pieces at the time the breccia was deposited. Petrographically the fragments are indistinguishable from many shales and silty shales of the Mam Tor Sandstones.

SOLE MARKINGS

Trail Casts

The following descriptions refer mainly to the sole markings inverted from their normal attitude in the depositional succession.

Casts of the trails and burrows of organisms are often found on the soles of sandstones at Mam Tor. The most common trail casts are straight to curving, interlaced, rounded ridges up to 5 cm in length and 5 mm in breadth. Towards their ends the ridges fade downwards. They may be scattered or closely packed and are widespread on the soles of many of the non-laminated and the laminated sandstones. Groove casts often cut the trail casts, proving the existence of the trails before the overlying sandstones were deposited.

The less common trail casts are loosely entwined cylinders of sandstone protruding from the sandstone soles. The cylinders reach 5 mm in diameter and, on polished sections, are seen to extend into the sandstones as infilled tubes. These trail casts are rarely widespread. They seem to be the backfilled burrows of organisms active after the sandstones were deposited.

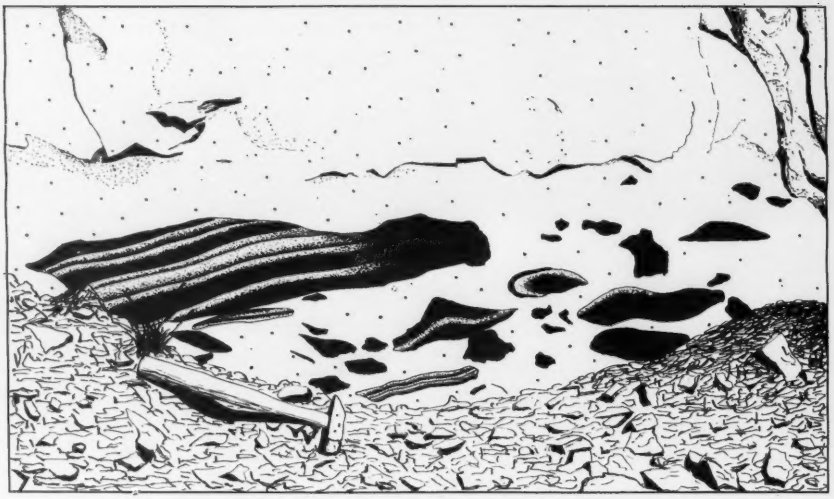

FIG. 4.—Shale breccia in non-laminated sandstone bed, Mam Tor Sandstones, Mam Tor. The hammer is 35 cm. After a photograph.

Groove Casts

Downward facing rectilineal structures known as groove casts (Shrock, 1948, p. 163; Kelling and Walton, 1957, p. 482) are the most common sole markings at Mam Tor, occurring in about half the sandstone-shale groups examined. They may be preserved in the non-laminated or the laminated sandstones and are borne by even the thinnest of the groups.

Three types of groove cast can be distinguished and occur together on the slab shown in figure 5. Many of the groove casts are delicate ridges evident only when obliquely lit. They reach 40 cm in length and rarely exceed 1 mm in height or breadth. From the highest point at or near the centre each ridge falls longitudinally to the surrounding sole. They are partly equivalent to the "bounce casts" of Wood and Smith (1959, p. 168).

Another common type of groove cast reaches 5 to 10 cm in breadth and 4 cm in height. These casts extend fully over the outcrops of the sandstone soles, distances sometimes of 5 m, and often bear parallel longitudinal ridges and striae. On each side of some of the casts lies a broad hollow marked by small, oblique, knotted ridges corresponding with a broadly rounded ridge on the original structure. The knotted ridges of the hollows form a V-shaped pattern symmetrical about each groove cast. At Mam Tor this pattern points westwards in the lower part of the succession, southwards in the upper part.

A very common type of groove cast rarely exceeds 5 cm in length. Each cast is bluntly raised at one end but towards the other slowly descends to meet the surrounding sole. The blunt ends are often rough or knotted, pointing westwards or southwards at Mam Tor. Wood and Smith (1959, p. 168) put these also under "bounce cast".

The three types of groove casts maintain a similar orientation on each sandstone sole, rarely lying farther than about 10° from each estimated mean trend. This was found to be true even when the casts were measured over outcrops nearly 800 ft in length. According to the part of the sequence examined, a dominant orientation of the casts was found when the sandstone-shale groups were lumped together. Figure 6 gives the orientation of 61 groove casts (second type) from 27 groups at Mam Tor. The beds (0 to 100 ft)

FIG. 5.—Groove casts on a sandstone sole, Mam Tor Sandstones, Mam Tor. Reading Univ. Dept. Geol. Mus. No. S 13004.

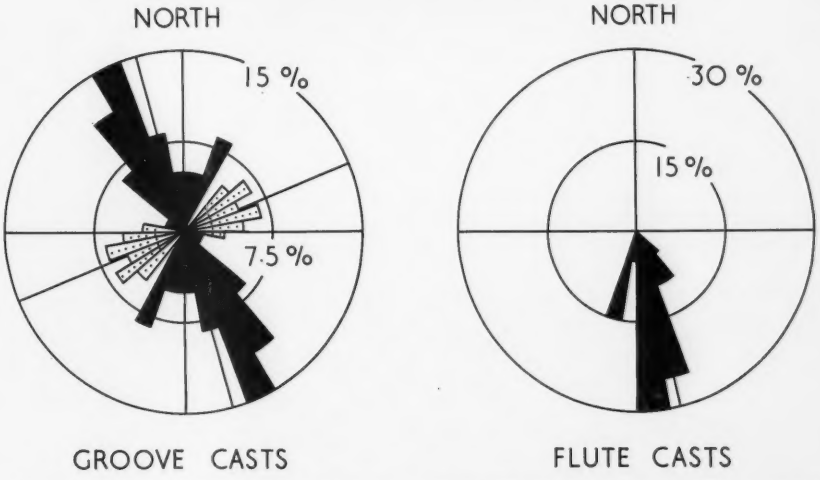

FIG. 6.—Rose diagrams showing the orientation of groove casts (below shale member, stippled; above shale member, solid) and flute casts (above shale member only), Mam Tor Sandstones, Mam Tor. Percentage frequencies are denoted by the diameters of the concentric circles.

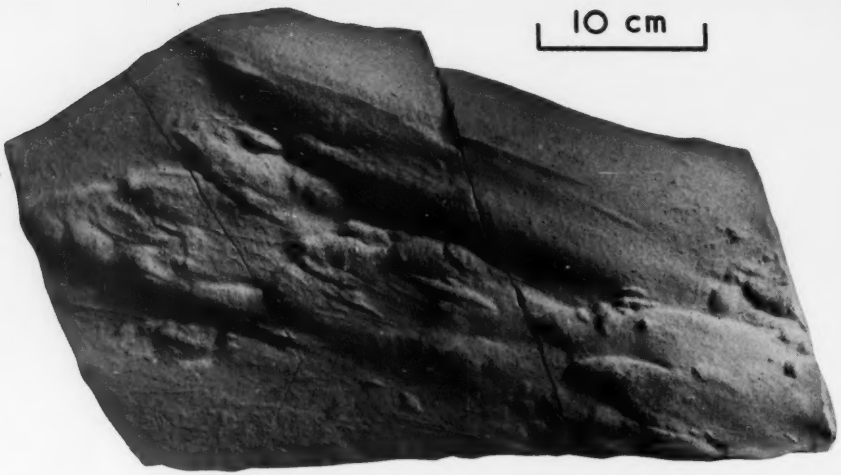

FIG. 7.—Flute casts on a sandstone sole, Mam Tor sandstones, Mam Tor. Reading Univ. Dept. Geol. Mus. no. S 13005-7.

below the black shales gave by vector summation a true mean of 68° (248°), changing abruptly to 168° (348°) in the higher strata (114 to 350 ft).

Flute Casts

The name flute cast (Crowell, 1955, p. 1359; Kelling and Walton, 1957, p. 482) has been given to elongated structures raised at one end commonly found on the soles of graded sandstones. Rücklin (1938) distinguished simple, flat, horseshoe, and corkscrew forms.

Flute casts are confined at Mam Tor to the thicker and coarser sandstone-shale groups (114 to 350 ft) above the black shale member. Typical casts are shown in figure 7.

The casts reach 5 cm in height and 30 cm in length. One end is rounded and sharply raised; the other fades gradually into the surrounding sole. The flute casts are chiefly found in clusters and less commonly in rows. The flat and simple flute casts of Rücklin (1938) are the most common, the horseshoe and corkscrew forms the least abundant. The transverse ridges on the corkscrew flute casts always twist dextrally. Groove casts are often present on the same soles. Sometimes the flute casts cut the groove casts; at other times they bear the groove casts. Polished sections of the flute casts often revealed concentrations of very coarse sand or granules at their raised ends.

The steepened ends of the flute casts in each row or cluster point in a single direction (north) while their long axes show a rough parallelism. All the flute casts on each sandstone sole have the same orientation. One dominant orientation of the casts was found in the aggregated sandstone-shale groups. Twenty flute casts from seven groups above the black shales gave the mean orientation of 166° (fig. 6), strikingly close to the trend of groove casts from the same beds.

Load Casts

Load casts (Kuenen, 1953a, p. 1048; "flow casts" of Shrock, 1948, p. 156) are sole markings consisting of lobes and tongues of sandstone. They are deformational structures, their form being determined often by earlier flute casts, groove casts, or ripple-marks (Kelling and Walton, 1957).

Load casts are most plentiful among the higher Mam Tor Sandstones. Sometimes balloon-like and of large size (40 cm diameter), the casts are scattered, clustered, or packed over the soles of many of the nonlaminated and the laminated sandstones. Typical load casts of about average size are

shown in figure 8. Although "flame" structures of shale deeply penetrate the contorted sole, the laminae in the sandstone remain parallel to the surfaces of the tongues and lobes. Some load-groove casts and load-flute casts occur at Mam Tor, but loading after ripple-mark is so far unknown.

Sludge Casts

Sludge casts (Wood and Smith, 1959, p. 169, pl. VI, 3, 4) are low, elongated, parallel grouped ridges rounded at one end. They are thought to be deformational structures related to load casts, although Kuenen (1957, fig. 9, pl. I, A) has figured almost identical forms as flute casts. Sludge casts, rarely plentiful, accompany load casts at Mam Tor.

GRADING

Grading, an upward decrease in grain size of the deposits, marks all the sandstone-shale groups at Mam Tor. The precise mode of the grading depends largely on the lithology and the total thickness of the sandstones present.

Where sandstones aggregate more than about 1 ft, the vertical succession of rock types is: (1) non-laminated sandstone, (2) laminated sandstone, (3) laminated siltstone, (4) silty shale, and (5) shale. The sandstones often bear shale conglomerates, sometimes breccias. Normally each group begins with a thin (<3 cm) graded layer of very coarse grains and granules resting sharply on the shales below. Grain size diminishes gradually and smoothly upwards in the coarse to medium grained non-laminated sandstones above. Non-laminated sandstones are always the predominant arenites in the thicker sandstone-shale groups, the proportion diminishing as the sandstones aggregate less.

Feebly laminated sandstones, laminated

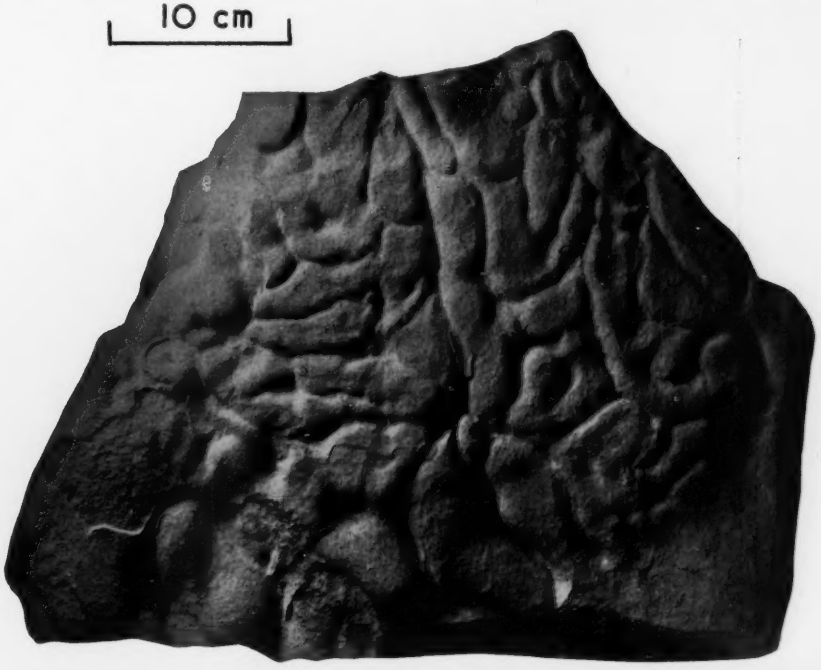

FIG. 8.—Load casts on the sole of a laminated sandstone, Mam Tor Sandstones, Mam Tor. Reading Univ. Dept. Geol. Mus. no. S 13008.

sandstones, and laminated siltstones follow the structureless deposits and continue more rapidly the reduction in grain size. The grading is now no longer smooth but proceeds discontinuously from lamina to lamina with many reversals in the trend, silty shales changing rapidly into thick uniformly graded shales to complete each group. Basal sandstones of the next group follow sharply.

The non-laminated sandstones are absent or very thin when the arenites of a group aggregate less than 1 ft. Typically, the grading then takes place through (1) laminated sandstone, (2) laminated siltstone, (3) silty shale, and (4) shale. A discontinuous layer of granules and coarser grains sometimes precedes the laminated sandstone. The grading through the sandstones and siltstones to the shale is rapid and broken by many slight reversals in the trend. As in the thicker groups, the shales are uniformly graded to the base of the group above. A few of the groups were observed to lack the shales, grading nonetheless being found in the sandstones present.

DEFORMATIONAL STRUCTURES

Convolute Bedding

Convolute bedding (Kuenen, 1952; Haaf, 1956) is preserved by the laminated portions of a number of sandstone-shale groups. The folds of the convolute bedding are flat lying to steeply inclined, and show no detectable preferred orientation of their axes. They reach 50 cm in length, die out downwards into horizontally layered non-laminated or laminated sandstones, and fade upwards into similarly bedded shales or silty shales. This suggests that the folding took place after the deposition of the overlying rocks had begun. Convolute bedding is widely persistent laterally in several of the groups. In one it was traced for 50 ft before dying out.

Corrugated Bedding

Corrugated bedding (Shrock, 1948, fig. 229, E) is distinguished from convolute bedding by the upward persistence, strengthening, and final transection of the folds. The folds die out downward just as in convolute bedding, but their truncation proves that they were formed before the overlying rocks.

Corrugated bedding is preserved in the laminated deposits of several thicker groups at Mam Tor. In one or two it is widely persistent laterally, a good example occurring 155 ft above the base of the succession. The folds are overturned, flat lying to steeply inclined, and reach a maximum length of 1.25 m normal to their axes. They fade downward into horizontally bedded non-laminated or laminated sandstones, become more complex upwards, and extend laterally for about 20 ft before dying out. The contorted layers, bent over towards the south, are truncated by the sharp load-cast sole of the sandstone above.

The folds of corrugated bedding at Mam Tor are chiefly overturned southwards, their axes normally trending east-west. Groove casts and flute casts, preserved in the same bed or in the bed above, often lie normal to the fold axes.

Crumpled Bedding

This structure is limited to the thinner sandstone-shale groups and is therefore preserved chiefly in the laminated deposits. Crumpled bedding involves all the arenaceous units of a group. It consists essentially of widely to closely spaced groups of folds connected by stretches of undeformed flat-lying beds. The folds are typically recumbent, less than 15 cm long normal to their axes, simple externally, and complex inside. The fold axes mainly trend east-west and the folds are often turned under towards the south. Distorted sole markings are sometimes found on the outer surfaces of the structures.

A good example of crumpled bedding occurs on the west shoulder of Mam Tor by the Edale road. One group of folds from this bed is shown in figure 9 and illustrates most of the important characters of the structure. The basal laminated sandstones of the parent beds give rise to the simple external shapes of the folds. Sole markings were not detected. The siltstones in one core are thrown into small faulted plications. Sections cut parallel to the axes and normal to the axial planes revealed closely spaced oblique faults.

Slump-ball structures

Rounded masses of contorted sandstone isolated in shale have been termed "slump-ball structures" (Kuenen, 1949, p. 269).

FIG. 9.—Section normal to fold axes through one group of folds from crumpled bedding, Mam Tor Sandstones, roadside on the crest of the west shoulder of Mam Tor. Reading Univ. Dept. Geol. Mus. no. S 13009.

Similar balls of sandstone, embedded in shale and laterally interspersed with undisturbed beds, occur in lines at several horizons at Mam Tor. Many of the balls preserve on their outer surfaces distorted trail casts or groove casts.

The slump-balls range to 50 cm in diameter and are normally formed by the laminated sandstones and siltstones. Many of the larger balls consist of piles of long flat folds broken by small-scale faults. Tongues of the enveloping shale penetrate between the folds. The noses of the folds almost invariably point southwards while their axes trend approximately east-west. Measurements on seven lines of slump-balls gave a mean axial trend along 101° (281°). The smaller slump-balls are chiefly spirals, less commonly saucer-shaped masses, of laminated sandstone or siltstone.

Part of a line of large balls is simplified in figure 10. The balls lie 115 ft above the base of the Mam Tor Sandstones, extend laterally for about 75 ft, and reach 50 cm in diameter. Each ball consists of flat piled-up folds separated by thin tongues of shale. Their outer surfaces bear trail casts. Small faults up to 5 cm in throw cut the trail casts and the laminae of each fold. One set of faults lies almost parallel to the axial planes of the folds and throws inward towards their cores. Another set, symmetrical about the axial planes, breaks the folds into prismatic blocks. The fold noses point southwards.

GENESIS

Source rocks

The Mam Tor Sandstones are the mixed deposits of two sources, the one extrabasinal, distant from the Namurian depositional site, the other intrabasinal and lying within the general area of sedimentation. The extrabasinal sources gave quartz, feldspar, schistose grains, microcrystalline silica, and mica. Granitic rocks and high grade metasediments therefore seem to have been present.

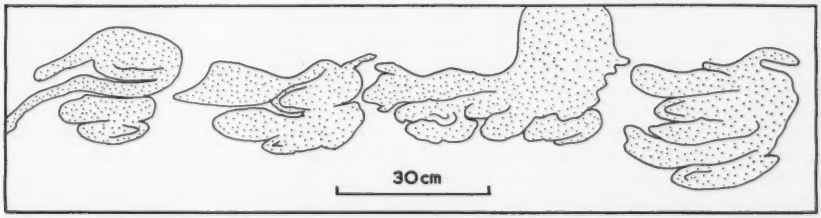

FIG. 10.—Slump-balls (stippled) of laminated sandstone and siltstone enveloped by shale. The section is roughly normal to the fold axes. After photographs.

Sorby (1859) and Gilligan (1920) have already described pebbles of schists, granites, pegmatites, "cherts", and other rocks from the Millstone Grit of Yorkshire. They agreed that most probably came from the Precambrian of Scandinavia, Gilligan thinking that the Scottish area might also have contributed.

From the intrabasinal source, contemporaneous or nearly so with the Mam Tor Sandstones, ill-consolidated muds and sideritic deposits were eroded. Their detritus was intimately mixed with the more far-travelled debris and then deposited at Mam Tor. The clay matrices of the sandstones may well represent the end-products of the resedimentation processes. The plant debris, originating in the swamps and perhaps subaerial parts of the Namurian basin, may also have been reworked.

Conditions of Deposition

The shales of the Mam Tor Sandstones are homogeneous, unlaminated, and locally rich in pelecypods. Goniatites have been recorded from the beds at localities to the north and northwest of Mam Tor (Hudson and Cotton, 1945, p. 153). These features all point to the deposition of the shales in a marine environment beyond the influence of waves and tides. Time and again sandstones were interpolated into these surroundings, each sandstone by the same abruptly appearing catastrophic agent of widespread uniform character. This is amply proved by the sharpness of the soles and the extreme lateral persistence of even the thinnest sandstone beds. After each sandstone had been deposited, the normal modes of tranquil sedimentation were gradually re-established.

The lack of stratification, the poor sorting, the abundance of clay matrix, and the frequency of large plant and shale fragments all suggest the fleeting existence and the high density of the currents which deposited the non-laminated sandstones. Evidently the particles in the currents were insufficiently well dispersed to make the individual responses to velocity fluctuations necessary for their good sorting. Likewise, the brief suspension of the particles will have tended to keep sorting to a minimum. A few of the non-laminated sandstones, however, are well sorted. This suggests either that some of the transporting currents were of low density or that well-sorted detritus only was available at certain times.

Since in all the sandstone-shale groups finer grained and better sorted deposits overlie those less well sorted and coarser grained, it follows that as deposition proceeded the density and velocity of the transporting currents slowly fell. The rate of sedimentation was high nevertheless. The ripple-drift bedding, characteristic of the siltstones and some sandstones, could have formed only if the grains had rained abundantly down onto a moving sand bottom. (Sorby, 1908, p. 184). Further evidence of the high rate of deposition is provided by the load casts. These are formed most often when hydroplastic muds are rapidly and unequally loaded, usually by sand (Shrock, 1948, p. 156; Kuenen, 1957, p. 246). The convolute bedding perhaps reflects similar adjustments effected more deeply in the stressed sediments. Finally, the grading indicates that conditions of sedimentation gradually returned to the stable state when only fine clays were deposited. The interpolation of the sandstones seems to have been intermittent for many of the uniformly graded shales are thick.

Other features of current origin are preserved at Mam Tor. The groove casts replicate grooves which Shrock (1948, p. 163) thought were formed generally "by simultaneous rectilinear advance of a squad of objects propelled by a current" over a surface of soft mud. Rich (1950, p. 725), Kuenen (1957, p. 245), and many others have also supported this view. The smallest of the groove casts at Mam Tor, fading down towards each end, are the counterparts of grooves which could have been made by sand grains and granules swept in gentle downward curves over a smooth mud bottom. The muds in some cases had already been marked by organisms. Deposition after grooving was often sufficiently rapid to preserve all these delicate structures.

Fragments of shale or plants dragged across the mud could have originated the larger and often striated groove casts. Dzulynski and Radomski (1955), indeed, found pieces of shale at the terminations of structures which they claimed were groove casts. Some of the shale fragments at Mam Tor,

however, must have been carried partly in suspension for they are not often found at the immediate bases of the sandstones. The patterned hollows associated with some of the large groove casts are probably the replicas of slices of mud successively cast up as the shale or plant fragments ploughed along. Some groove casts are raised and knotted at one end. They were perhaps originated by flat fragments which at first lightly grooved the mud but then caught in it and, twisting in the current, were sharply removed due to the increased drag without grooving further. Finally, the orientation of the groove casts at Mam Tor suggests that at first the currents flowed roughly westwards. After a period of shale formation, the main southerly currents depositing the greater part of the succession were established.

Clarke (1918) suggested that flute casts are the counterparts of erosional hollows elongated parallel to the current and deepest at the up-current end. The work of Rücklin (1938, p. 110), Rich (1950, p. 725), Kuenen (1953b, p. 25; 1957, p. 241), and Crowell (1955, p. 1360) has amply substantiated this view. An identical interpretation is placed on flute casts at Mam Tor, their orientation (steep ends roughly north) proving that most of the graded beds were deposited by southerly currents.

Most of the more important features of the Mam Tor Sandstones can be explained by the hypothesis that intermittent turbidity currents (Bell, 1942; Kuenen, 1951, 1953a, 1957; Kuenen and Migliorini, 1950; Kuenen and Menard, 1952) rapidly deposited the sandstones in a deep marine environment where clays were normally being slowly formed. This hypothesis satisfactorily accounts for the sharp soles, the extreme lateral persistence, the high rate of deposition, the poor sorting, and the current structures of the sandstone beds. In addition, it explains the contrast in each sandstone-shale group presented by the terriginous aspect of the sandstones and the thoroughly marine character of much of the shale.

Submarine slopes are essential to the movement of turbidity currents The main currents at Mam Tor seem to have run westerly then southerly, suggesting that the sea floor of the time fell towards the west and later the south. Independent evidence of the submarine slope is afforded by the corrugated bedding, the crumpled bedding, and the slump-ball structures. The corrugated bedding probably arose by the slipping of the laminated deposits over the relatively more unyielding sands soon after deposition. The crumpled bedding suggests that some beds were actually shortened during gliding. The common east-west trend of the fold axes of both structures points to movements chiefly normal to this direction. Since the fold noses point south, the slipping took place on surfaces whose main slope was probably from north to south. The slump-ball structures point to the extensive sliding of some thin sand beds. The orientation of their folds is also consistent with movements on north to south slopes.

Regional Setting

The Mam Tor Sandstones and Shale Grit lie in the *Reticuloceras reticulatum* Subzone of the Namurian (Hudson, 1945; Bisat and Hudson, 1941, p. 287, 289; Hudson and Cotton, 1943, p. 153). The formations thin to the south and southwest of the Peak District and seem to be replaced finally by shales (Green and others, 1887; Fearnsides and others, 1932, p. 168). Northward the Mam Tor Sandstones and Shale Grit appear to maintain their individuality as far as the Holmfirth and Rochdale districts (Mid-Pennines). Here they pass into thick coarse sandstones of *R. reticulatum* age (Bisat and Hudson, 1941, p. 433; Stephens and others, 1953, p. 33). Lower sandstones of the subzone of this area are variously named the Todmorden Grit, Caley Crags Grit, or Lower Plumpton Grit. A higher sandstone is called the Addingham Edge Grit or Upper Plumpton Grit.

The Grits form facies distinct from those of the flysch-like Mam Tor Sandstones and Shale Grit. The occurrence of thick cross stratified and flaggy beds, the very coarse sand to granule grade of the sandstones, the presence of pebbly seams and swamp-plant debris, and the association with authochthonous coals all suggest the shallow water and fluvial origin of the Grits. Walker (1955) has measured cross-stratification dip directions on the Caley Crags Grit and Addingham Edge Grit at localities in the Mid-Pennines between Burnley, Leeds, and Harrogate. He

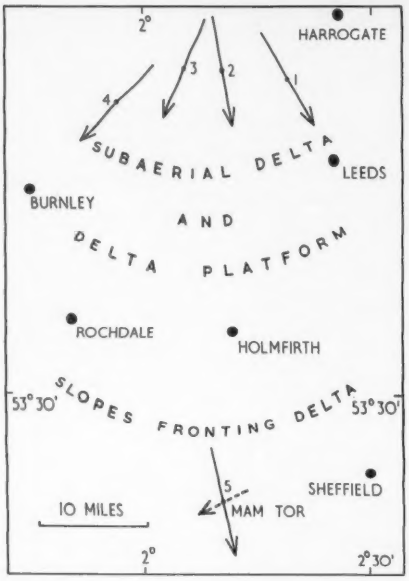

FIG. 11.—Current directions during deposition of Mam Tor Sandstones (5), Caley Crags Grit, (1), and Addingham Edge Grit (2, 3, 4) and the tentative distribution of facies in sediments of the *R. reticulatum* Subzone (Namurian) in the Millstone Grit, Peak District and Mid-Pennines.

showed that the Grits had been deposited by southeasterly to southwesterly flowing rivers. The directions of main current flow and sediment supply, calculated from Walker's (1955, p. 121, table 3) data, are shown in figure 11. They are strikingly close to the main directions determined from the Mam Tor Sandstones of the same age.

A tentative synthesis (fig. 11) of the data available from the Peak District and the Mid-Pennines suggests that the sediments of the *R. reticulatum* Subzone were derived from northerly sources and were deposited in the mixed marine and deltaic environments of a southerly deepening basin. The coarse coal-bearing sandstones and marine shales developed north of Rochdale and Holmfirth seem to represent the shallow marine, brackish, and freshwater environments of the delta-top and delta-front. The Mam Tor Sandstones to the south indicate that a submarine surface fronted the shallow delta and descended to neritic and perhaps bathyal depths. On this surface, at intervals during the sedimentation of clays, southerly-flowing turbidity currents can be suggested to have deposited coarse sands replete with terriginous and resedimented detritus. These currents perhaps originated in slumps of the mixed coarse and fine sediments laid down on the delta-front. In a marine basin to the extreme south and southwest, apparently beyond the reach of the underflows, the quiet sedimentation of clays proceeded.

CONCLUSION

The likely deposits of turbidity currents, the "turbidites" of Kuenen (1957, p. 231), have been recognised widely in many parts of the world. Most seem to have been formed under marine conditions, often far from shore, in deep geosynclinal basins later involved in orogenic folding. The graywacke successions of the British Lower Palaeozoic geosynclines now afford well-documented illustrations of this perhaps typical mode of occurrence. In these and other cases (Carozzi, 1957; Cope, 1959; Cummins, 1957; Kuenen and Carozzi, 1953; Natland and Kuenen, 1951; Phleger, 1951; Shepard 1951) it can be suggested that the immediate sources of the "turbidites" lay in the shallow water deposits of the same basins.

Rarely, however, can these source sediments be found in the field. The occurrence of shallow water sandstones lying up-slope from coeval graded graywackes in the Kulm and Flozleeres of Germany (Kuenen and Sanders, 1956, p. 660) is one noteworthy exception.

The main interest of the Mam Tor Sandstones is that a similar relationship can be suggested, in this case within a body of broadly deltaic rocks. Clearly, the time has come for the closer scrutiny of Namurian deposits of the South- and Mid-Pennines, for even the major sedimentological features of the Millstone Grit deltas are not yet well known.

ACKNOWLEDGMENTS

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FIGS. 1–5, JUNE, 1960

FORE-REEF PETROGRAPHY OF THE SILURIAN RICHVALLEY REEF, INDIANA[1]

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ABSTRACT

The microscopic investigation of the inclined fore-reef beds of the Silurian Richvalley reef (developed in the Liston Creek Formation) reveals that they consist of five microfacies. These appear today through the effect of dolomitization as argillaceous dolomites, dolomites, dolomitic calcarenites and calcarenites; however, they all were originally calcarenites.

The statistical investigation of the detrital quartz, the echinoderm fragments, and the general organic frequency allows a bathymetrical classification of the five microfacies indicating that each tongue of fore-reef clastics consists of their juxtaposition in concentric belts. Hence, it is possible to reconstruct the fluctuations of the reef-core margins corresponding to the successive tongues.

INTRODUCTION

The purpose of this study has been to describe the textural variations in the inclined fore-reef beds of the Silurian Richvalley reef (developed in the Liston Creek Formation) and their possible use to outline the position of the reef core.

The field work consisted of the establishment of five vertical sections including all the fore-reef beds exposed, so that the top of each section could be correlated obliquely down-dip to the bottom of the next one (fig. 1). A first series of 88 oriented samples was collected from the base and the top of each bed and also at 1-ft intervals wherever the thickness of the beds allowed additional sampling. A second set of 115 oriented samples was taken at 5-ft intervals within each bed to check the lateral correlations and changes in texture. Each thin-section made from the collected samples has been statistically analyzed and classified as to microfacies on the basis of microscopic texture, mineral content, and organic content. The variations of the microscopic parameters were plotted on appropriate scales and their environmental significance interpreted.

Examination of the thin sections disclosed that microfacies persisted through more than a single bed as viewed in the field and also crossed bedding planes. Therefore, the recognition of individual beds as well as microfacies would cause considerable confusion, and the former has been discarded in favor of an interpretation solely on the basis of the microfacies.

[1] Manuscript received September 3, 1959.

GEOGRAPHIC LOCATION AND GENERAL DESCRIPTION

The area investigated is located in Wabash County in northeastern Indiana (Esarey and Bieberman, 1949). The particular reef under consideration is located in SE ¼, NE ¼, sec. 13, T. 27 N., R. 5 E., 1 mile east of the Richvalley railroad station where a topographical high has been cut through by the east-west railroad and crossed by the north-south U. S. Route 24. The exposure made by the railroad cut is more than 1500 ft long extending in a direction just north of east; the exposure is approximately 15 ft high. It consists, in essence, of two parts. The eastern part of approximately 390 ft is composed of a series of easterly dipping fore-reef beds which in total are approximately 90 feet thick. Dips are variable, being 20 to 25 degrees on the west end and increasing to a maximum of 35 degrees near the east end (fig. 1). After reaching this maximum, the beds assume a westerly dip of 8 to 14 degrees. This reversal of dip is not an uncommon phenomenon in Niagaran reefs and is believed by Cumings and Shrock (1926, 1928) to result from the settling of the heavy reef masses into the underlying sediments.

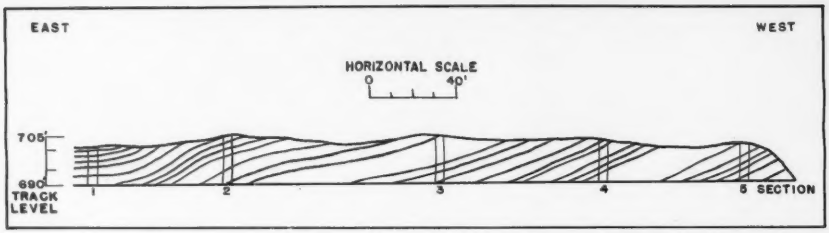

FIG. 1.—Composite diagram showing field relations between sampled sections.

The western part of the exposure displays a series of small, isolated, knob-like structures corresponding to parasitic reef-growths. Some finely varved beds are present as well as pockets of slumped and contorted shales. After an initial survey this part of the section was abandoned because the nature and spacing of the outcrops would not furnish any additional information.

Lithologically, the fore-reef beds appear as argillaceous dolomites, dolomites, dolomitic calcarenites, and calcarenites. However, all the dolomitic members correspond under the microscope to the products of secondary dolomitization of calcarenites. In other words, the entire set of fore-reef beds consisted originally of various types of calcarenites. The bedding planes are slightly undulated, and chert may be present as nodules or as an irregular network parallel to the bedding. Neither the reef-core nor the inter-reef facies of the Liston Creek Formation are exposed in the railroad cut. The relations between the position of the latter, the general topography, and the indications given by two other adjacent quarries indicate that the reef-core is located south of the investigated cut.

METHODS AND TECHNIQUES OF INVESTIGATION

The following parameters (Carozzi, 1958) were measured in thin-sections:

Maximum apparent grain-size (clasticity-index) and frequency of the detrital quartz.—The maximum apparent grain-size is representative of the local intensity of the currents or of the agitation whereas the frequency indicates the load of particles present at a given point. The latter has been measured in this study over six randomly distributed fields of view under a medium power objective, corresponding to a total area of 18.9 sq. mm.

Maximum apparent diameter and frequency of echinoderm fragments.—This very abundant organic component was investigated for itself. The frequency was determined over six fields of view, randomly selected, with a low power objective, corresponding to a total area of 198 sq. mm.

General organic frequency.—In addition to echinoderm fragments which apparently are very resistant to dolomitization, thin-sections show remains of corals, bryozoans, pelecypods, calcareous algae, and ostracods. These components have been affected by dolomitization to a very variable degree which complicates their statistical computation. Under such circumstances, it appeared convenient to express only the frequency of the total organic population excluding the echinoderms. Such a frequency was measured with a low power objective over six fields of view, randomly selected and corresponding to a total area of 198 sq. mm.

Dolomite frequency.—The degree of dolomitization of the carbonate content of each sample was determined by a method similar to that suggested by Tennant and Berger (1957). A relative uniformity of particle size was insured by passing the pulverized rock material through a 200-mesh screen.

The screened product was placed in an aluminum slide and X-rayed through a 2θ angle of 5 degrees (27 to 32 degrees). The main calcite peak occurred at 29.39° and the dolomite peak at 30.96°. A ratio, calculated from the relative intensities of the calcite and dolomite peaks, determined the percentage of dolomite present.

The calcite and dolomite peaks of the samples were compared to peaks obtained from standards of similarly prepared mixtures of pure calcite and dolomite mixed in varying proportions from pure dolomite to pure calcite with intermediate stages progressing on the order of 10 percent calcite per sample until pure calcite was reached. In theory, a comparison of the peaks of the unknown samples with those of the standards should reveal an approximate value for the former. In practice this is not successful because the standards were prepared from samples of carbonate uncontaminated by impurities, whereas the unknown samples are contaminated to varying degrees by silica, clay minerals, and possibly other materials. The peaks received from X-ray diffraction, therefore, lacked the intensity of those obtained from pure carbonate samples. Direct correlation being impossible, the peaks for calcite and dolomite were then calculated on the basis of 100, and the percentage of dolomite was then computed from this calculation. The resulting answer represented only the amount of carbonate material dolomitized.

DESCRIPTION AND INTERPRETATION OF THE MICROFACIES

Petrographic analysis of the thin sections revealed five distinct microfacies (fig. 2) into which the fore-reef beds could be divided.

Microfacies 1.—Medium-grained, well-bedded, unsorted, calcarenite with a fine-grained matrix. The organic fragments consist of echinoderms, ostracods, calcareous algae, and foraminifera. Small pigments of pyrite are scattered throughout the slide.

Microfacies 2.—Fine-grained, well-bedded, unsorted, dolomitic calcarenite with a dark, granular matrix. Light-colored organic fragments (some of which are echinoderms; others are indistinguishable) are scattered throughout. Dolomitization has destroyed most of the larger organic fragments; as a result the original sediment which was a calcarenite coarser than microfacies 1 appears now as a fine-grained dolomitic calcarenite.

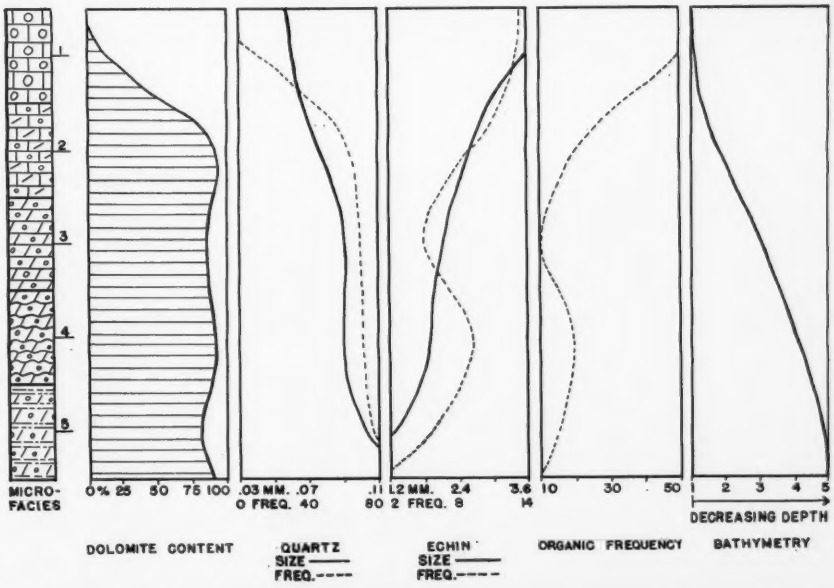

FIG. 2.—Diagram showing variations of mineral and organic parameters with microfacies.

Microfacies 3.—Fine-grained, well-bedded, dolomite with "ghosts" of large organic fragments tentatively identified as pelecypods and echinoderms. The dolomitization has been carried very far in this microfacies which appears to have been originally a calcarenite coarser than microfacies 2.

Microfacies 4.—Fine-grained, chaotic-bedded dolomite containing numerous scattered organic fragments that are largely recrystallized and appear to be predominantly echinoderms. This microfacies is again a dolomitized chaotic calcarenite, and its texture is emphasized by an irregular distribution of clay particles.

Microfacies 5.—Fine-grained argillaceous dolomite with numerous pyrite and clay pigments. Organic fragments (mostly echinoderms and pelecypod tests) are scattered and rare. The rock is a dolomitized argillaceous calcarenite.

The above-described calcarenites 1 to 5 have been listed in the order of original increasing grain-size which has been strongly modified and even reversed by the effect of secondary dolomitization. This order, which corresponds to deposition from deepest to shallowest conditions along the slope of the fore-reef talus, is also confirmed by the variations of the microscopic parameters (fig. 2).

Dolomite content.—The average dolomite content (fig. 2) starts at a minimum in microfacies 1; it then increases rapidly in microfacies 2 and displays only slight variations throughout microfacies 3 and 4. A small decrease in the average dolomite content, caused by a greater abundance of chert in the argillaceous dolomites and their related preservation effect of original calcareous material, is noted in microfacies 5.

Maximum apparent grain-size and frequency of detrital quartz.—Detrital quartz frequency (fig. 2) displays a minimum value in microfacies 1 followed by a rapid increase in microfacies 2. The values of frequency continue to increase in a regular way through microfacies 4 and 5, reaching maximum values in the latter. The variations of the quartz frequency are closely paralleled by the maximum apparent grain size (fig. 2) which is at a minimum in microfacies 1 (0.05 mm). It increases regularly through microfacies 2 (0.065 mm) and microfacies 3 (0.080 mm), remains nearly constant in microfacies 4 (0.080 mm), and increases again to a maximum in microfacies 5 (0.096 mm).

The detrital quartz originated from the shallowest zone, as indicated by its increasing clasticity and frequency from microfacies 1 to microfacies 5. The detrital supply was regular, accounting for the parallelism between the curves of size and frequency. This rather peculiar origin of the quartz and the clay particles is probably the result of current patterns which only a generalized paleogeographic study would be able to elucidate. Generally the quartz grains seem to originate from the inter-reef deposits (Carozzi and Zadnik, 1959).

Echinoderm variations.—In near opposition to the detrital quartz is the trend of the organic components, both echinoderms and general organic frequency which have a similar behavior (fig. 2). This near opposition is by itself an indication that the organic components of the fore-reef calcarenites are predominantly not mechanically transported. On the other hand, dolomitization does not account for their variations since changes of frequency follow a definite trend of their own, whereas the amount of dolomitization is practically constant from microfacies 2 to 5.

The maximum frequency of the echinoderms occurs in microfacies 1 and is followed by a general decrease until microfacies 5 with, however, an increase corresponding to microfacies 4. In general, the frequency increases with increasing depth as if the abundance of echinoderms were greater at the base of the fore-reef slope than at more elevated positions; this is probably caused by the increased amount of agitation and the increase of terrigenous material in the shallower waters.

The size of the echinoderm plates is at a maximum in microfacies 1 and probably approaches the average size of echinoderm plates liberated by the decomposition of the tests in place after death. The size decreases from microfacies 1 to 5 and trends generally parallel to the frequency with the exception that it does not show any increase in microfacies 4.

It is evident from the relations between the curves of the echinoderms and those of the quartz that mechanical transportation is not the predominant factor in the distribution of the echinoderm fragments; if this were the case, the curves of the two components

should be parallel. The echinoderm frequency curve can be explained by a combination of the effects of agitation in place and environmental influence. Because of the preference of the echinoderms for quiet, clear waters, it may be assumed that the less disturbed conditions of microfacies 1 were more favorable for their development than were the progressively shallower and turbulent waters corresponding to the other microfacies. As a result the frequency of the echinoderm fragments decreases where depth decreases and where agitation and amount of material held in suspension increase. The rather strong agitation displayed by the chaotic bedding in microfacies 4 corresponds to a maximum in place fragmentation of the echinoderm debris and accounts for the local peak in the frequency curve.

The size curve of the echinoderm fragments decreases as a whole from microfacies 1 to 5 and indicates that with decreasing depth and increasing agitation the plates were broken in place into smaller and smaller debris.

General organic frequency.—The general frequency of organisms (fig. 2) in general decreases from microfacies 1 to microfacies 5 in a manner parallel to that of the echinoderms; a local peak is also displayed in correspondence to microfacies 4. Apparently similar factors have affected the echinoderms and the other organic components. In other words, the latter were also more abundant in deeper, less agitated waters of microfacies 1 and decreased in frequency in the shallower waters. In place agitation with related fragmentation of the organic particles explains the increased frequency in microfacies 4.

Bathymetrical interpretation.—The combination of the above-described microscopic components with the textural variations indicates that the microfacies, when classified in order of decreasing original grain-size and of decreasing quartz clasticity are also arranged according to increasing water depth and appear to build concentric belts around the reef-core. Microfacies 1, then is representative of the deepest conditions of deposition and microfacies 5 of the shallowest (fig. 2).

It should be pointed out that this suite of fore-reef calcarenites are actually made up by two petrographic phases, an inorganic and an organic one. The former corresponds to reef-core fragments, detrital quartz and clay which were mechanically distributed down the slope with decreasing grain-size away from the reef-core. The latter phase, consists predominantly of fragments of echinoderms, which populated the detrital talus with a frequency reaching its maximum in the deepest conditions and decreasing with decreasing depth. The size of the other organic fragments shows a similar decrease as a result of increasing fragmentation in place related to agitation.

DESCRIPTION AND INTERPRETATION OF INDIVIDUAL SECTIONS

Section 1.—This section (fig. 3) is predominantly formed by microfacies 2 with only the upper foot consisting of microfacies 3. The dolomite content is consistently high throughout the section with a clear decrease where chert is present in microfacies 2.

Quartz clasticity and frequency are approximately parallel throughout the section, but the frequency oscillates more than the grain-size; the former slightly decreases upwards.

Echinoderm size and frequency are also nearly parallel, the more variable being the frequency which fluctuates from extreme values rather rapidly; both parameters increase upwards. A similar trend is shown by the organic frequency.

The bathymetrical interpretation indicates a depth decrease upwards.

Section 2.—This section (fig. 3) displays alternating microfacies 2, 3, and 4. The dolomite content is high in the entire section. Quartz clasticity and frequency are parallel and oscillate with decreasing values upwards. The echinoderm size and frequency are parallel and often opposed to the quartz curves. The frequency of the echinoderms increases upwards quite regularly whereas the size does the same with the exception of two strong peaks in the lower portion of the section.

The organic frequency also increases gradually upwards.

The bathymetrical interpretation reveals two oscillations with the deepest term as microfacies 2 and the shallowest as microfacies 4.

Section 3.—This section (fig. 3) is predominantly made up by microfacies 5 with only its lowermost portion consisting of micro-

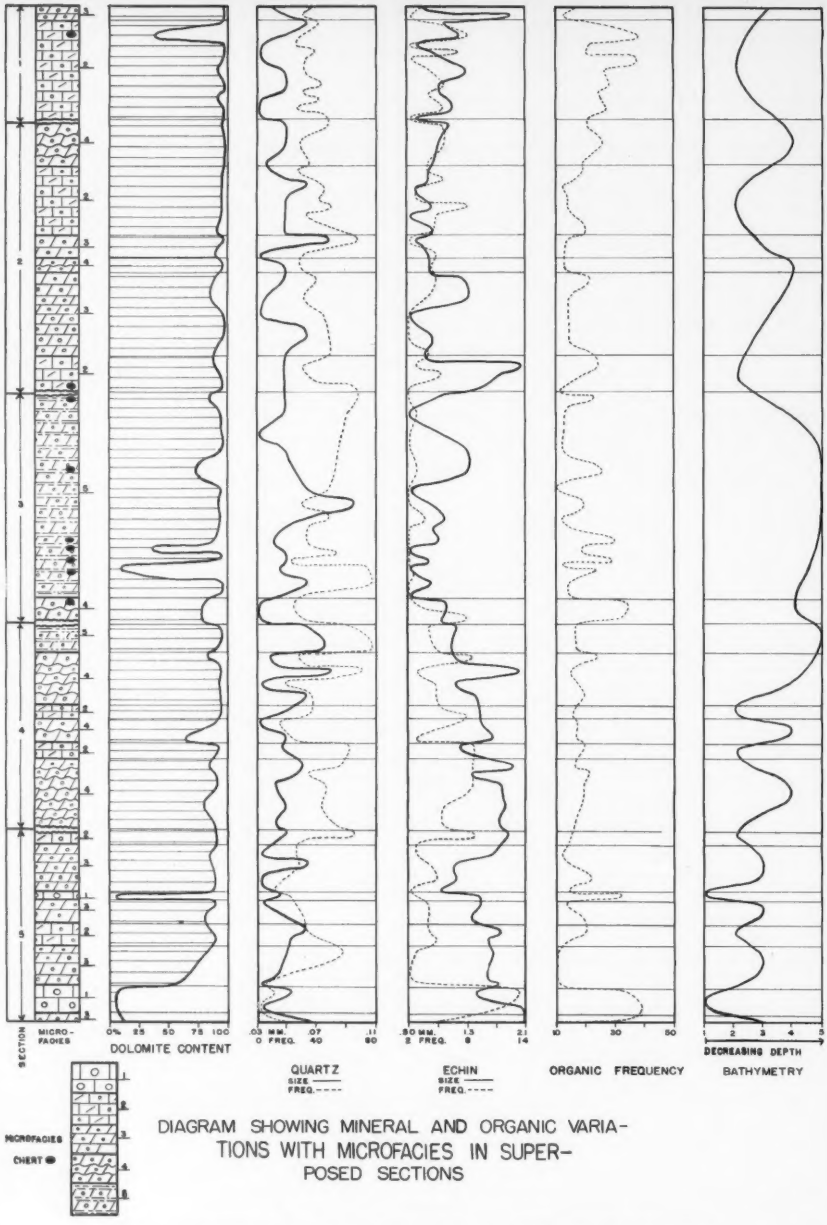

FIG. 3.—Diagram showing variations of mineral and organic parameters with microfacies in superposed sections.

facies 4. Considerable variation occurs in the dolomite content with low values always in relation with the presence of chert nodules.

Quartz clasticity and grain-size oscillate very strongly throughout this section, sometimes in opposition to one another; clasticity reaches its highest values in the middle of the section, but the frequency shows no definite trend.

The echinoderm size and frequency curves oscillate rather regularly in a parallel way, and display very low values strongly contrasting with the high values of the quartz curves.

The organic frequency also oscillates in the low field values and tends to decrease slightly upwards.

The bathymetrical interpretation indicates a rapid shallowing at the bottom of the section from microfacies 4 into 5 and stability during deposition of the latter.

Section 4.—This section (fig. 3) consists predominantly of microfacies 4 associated with microfacies 2 and 5. The dolomite content fluctuates slightly with a marked decrease in the middle of the section.

Quartz clasticity and frequency display a very close parallel variation particularly in the upper half of the section; both values increase upwards.

The echinoderm size and frequency do not display a very clear parallelism in their variations, but both definitely decrease upwards.

The organic frequency is rather uniform and does not show any clear trend.

The bathymetrical interpretation reveals three oscillations, the first and the second reaching microfacies 4 and the last one reaching microfacies 5.

Section 5.—This section (fig. 3) consists of alternating microfacies 1, 2, and 3. The dolomite content reaches a minimum in microfacies 1 and is also relatively low in microfacies 3 at the base of the section. Excluding these minima, the dolomite content is fairly high though it never reaches the high values described in sections 1 to 4.

Quartz clasticity strongly oscillates but

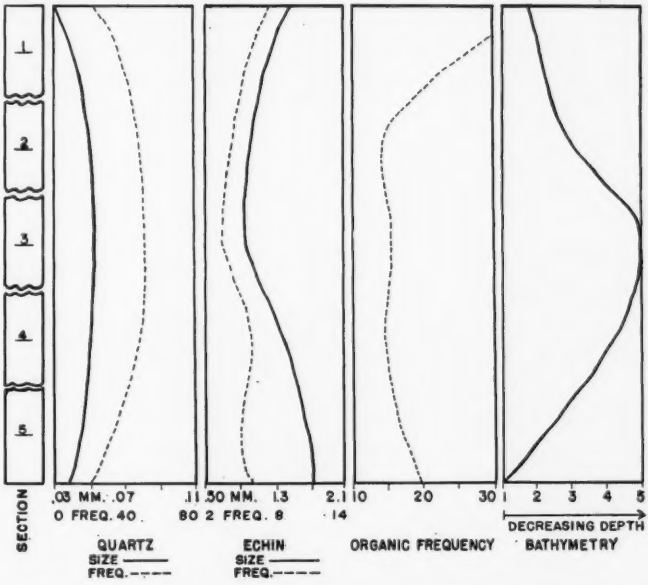

FIG. 4.—Diagram showing curves of main trend of quartz and organic parameters in superposed sections.

increases slightly upwards; its frequency increases also in the same direction but more strongly.

The echinoderm size and frequency tend to decrease upwards, the frequency decreasing more rapidly than the size. The organic frequency displays a rapid decrease upwards.

The bathymetrical interpretation shows irregular oscillations reaching three times microfacies 3.

GENERAL INTERPRETATION OF THE SUPERPOSED SECTIONS

Until now the five investigated sections have been described and interpreted as separate entities. They can, however, be superposed into a composite section (fig. 3) since they are actually younger from 5 to 1 and adjacent sections are correlated obliquely from top to bottom. The building of such a composite section assumes that the effect of the lateral displacement due to the position of the sections is much smaller than the lateral textural changes in the fore-reef beds.

The composite section reveals a very striking general evolution in time of all the parameters (fig. 3). This evolution can be emphasized by drawing the curves of main trend which are obtained by reducing for each section the different parameters to their average values (fig. 4).

Quartz clasticity and frequency increase from section 5 to 3, and after culmination in section 3 decrease again toward section 1. The main trend of the size and frequency of the echinoderms starts with high values in section 5, decreases to a minimum in section 3, and increases again upwards into section 1. A similar variation is displayed by the organic frequency with, however, a stronger increase from section 2 to 1.

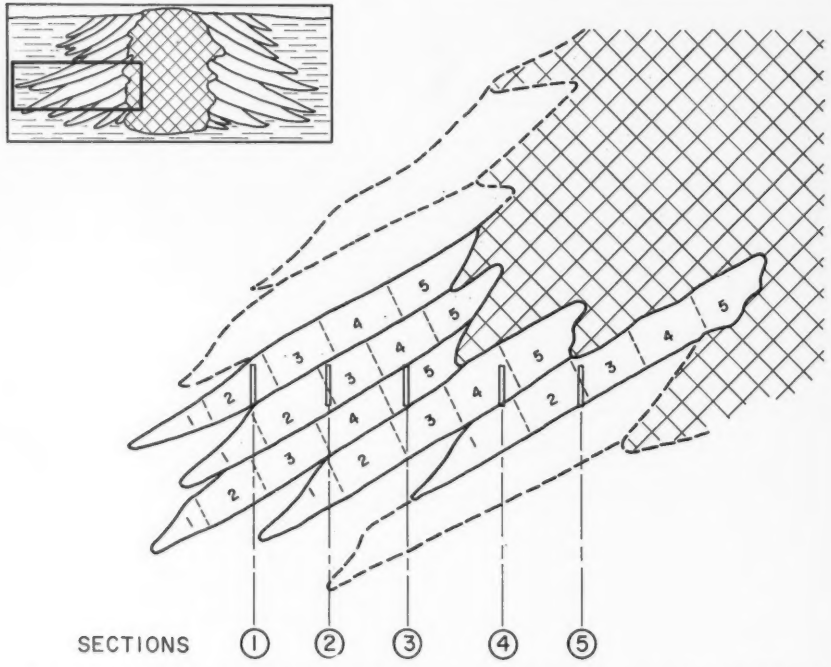

FIG. 5.—Idealized diagram showing relations between sampled sections, microfacies building inclined fore-reef tongues, and position of reef-core margins. Insert shows relation of the diagram to a vertical section of a typical Silurian reef in Indiana.

The main trend of the bathymetrical variations indicates a continuous depth decrease from section 5 to the shallowest conditions in section 3. This peak is followed by a depth increase upwards toward section 1 in which, however, the depth does not reach the values of section 5.

Table 1 shows in percentage of thickness, the microfacies which comprise the different sections and the predominant microfacies around which the bathymetrical oscillations have taken place in each case.

TABLE 1.—*Relation of microfacies in sections 1–5*

Sections	Microfacies				
	1	2	3	4	5
1	—	*90*	10	—	—
2	—	*40*	*35*	25	—
3	—	—	—	10	*90*
4	—	15	—	*70*	15
5	20	*25*	*55*	—	—

INFERRED POSITION OF THE REEF CORE

In our idealized diagram (fig. 5), each section is represented by its predominant microfacies as shown in table 1. Each tongue of fore-reef clastics consists of the juxtaposition of the five investigated microfacies in concentric belts ranging from microfacies 5, the shallowest, to microfacies 1, the deepest. The boundaries between juxtaposed microfacies are rather complicated by reciprocal intertonguing but have been drawn as straight lines in the diagram. For instance section 2 appears to be cut obliquely by the boundary between microfacies 2 and 3; this means that the section is predominantly made up by alternating beds of these two microfacies.

Figure 5 also shows that the bathymetrical evolution in time revealed by the composite section (figs. 3 and 4) may be interpreted as the result of the interference between the position of the five sections and the amount of lateral growth of the reef-core. It is thus possible to reconstruct the fluctuations of the reef-core margins corresponding to the successive tongues of fore-reef clastics.

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FIGS. 1–10, JUNE, 1960

SEDIMENTATION UNITS IN SANDSTONES OF THE YOREDALE SERIES (LOWER CARBONIFEROUS) OF YORKSHIRE, ENGLAND[1]

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ABSTRACT

The typical sandstone of the cyclothems of the Yoredale Series is a sheet sandstone which consists of a number of tongues of massive, cross-bedded sandstone lying on more continuous flaggy sandstone into which they pass laterally. Each tongue of massive sandstone has its origin in the bank of a channel sandstone, and the radially distributed cross-bedding of the massive sandstone can be used to locate the point of origin.

Local relief existing before sandstone deposition and that created by sandstone deposition can be demonstrated. The latter often was sufficiently pronounced to cause emergence of the surface of the sheet sandstone. The emergence is revealed by the occurrence of seat-earths, coals, and sandy patches in the overlying thin limestones.

The features described compare so closely with crevasse deposits in the Mississippi delta that there can be no doubt of their deltaic origin.

INTRODUCTION

Investigation of directional structures in sandstones has become one of the most important tools of the stratigrapher in recent years. Current directions, whether of wind or water, can be readily determined from analysis of sedimentary structures. The position and orientation of shorelines may be deduced from studies of oscillation ripplemarks. Investigation of cross-bedding on a regional scale may reveal the direction of inclination of the continental slope.

Early investigators of sedimentary structures (Shotton, 1937; Reiche, 1938; McKee, 1940, 1945) confined their attentions to the structures alone, but in the last decade there has been a welcome broadening of scope to include other aspects of the lithology of the rocks studied. Potter and Siever, both separately and in combination with other workers (1953, 1954, 1956, 1957, 1958), added petrographic analysis to regional sampling of cross-bedding to assess the source areas of the Pennsylvanian sandstones of the Central United States. An even more detailed study by Schwarzacher (1953) correlated amplitude of cross-bedding with grain-size in Lower Cretaceous sandstones from eastern England.

The work to be described in this paper integrates sedimentary structures and lithological variation in the clastic rocks of the Yoredale Series cyclothems in order to reconstruct individual sedimentation units. For the most part the study is concerned with the sandstones, because it is only in these coarse clastics that megascopic directional structures are at all common and are preserved in anything like their original condition. The study was further limited to the type area of the Yoredale Series so that the vertical coverage could be extensive enough to show which were the important features in the sedimentation units. The location of the type area and the distribution of the Yoredale Series outcrop within it are shown in figure 1; a detailed account of the stratigraphy is to be found in an earlier paper (Moore, 1958).

STRATIGRAPHY OF THE YOREDALE SERIES

The Yoredale Series, whose upper limit coincides with the base of the Upper Carboniferous, is divisible into eight major cyclothems and a variable number of minor cyclothems (Moore, 1959). An approximate section of the Series is given in figure 2 which shows the most important subdivisions in the type area. The proportion of sandstone varies greatly from cyclothem to cyclothem and within cyclothems. Excepting Cyclothem I, the major cyclothems show striking uniformity in their sandstones. Cyclothem I contains no sandstone in this area.

Each cyclothem, major or minor, comprises the following eight members:

[1] Manuscript received September 2, 1959.

8. upper shale
7. coal
6. seat-earth
5. massive sandstone
4. flaggy sandstone
3. siltstone
2. shale
1. limestone

None of the members is wholly persistent. The limestone, member 1, tends to persist in the opposite direction to the other members, which may be grouped together as the clastic members of the cyclothem. Of these clastic members, 7 and 8 are least extensive; together with member 6, their occurrence is dependent upon the presence of sandstone in

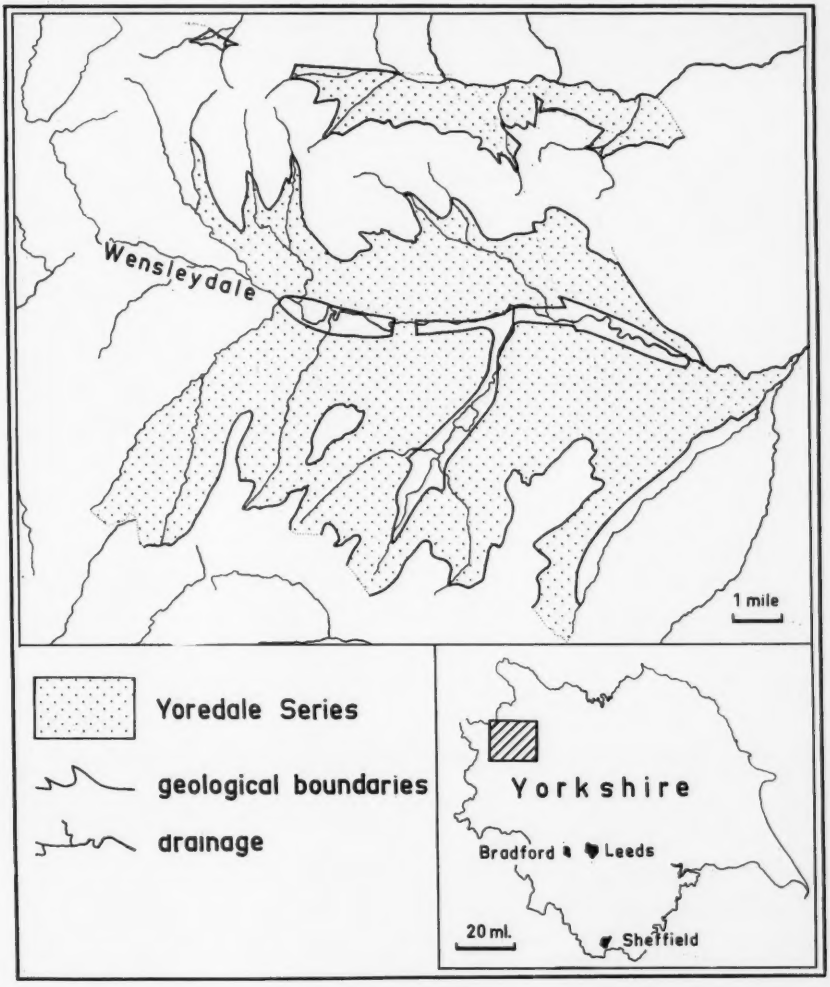

FIG. 1.—Locality map.

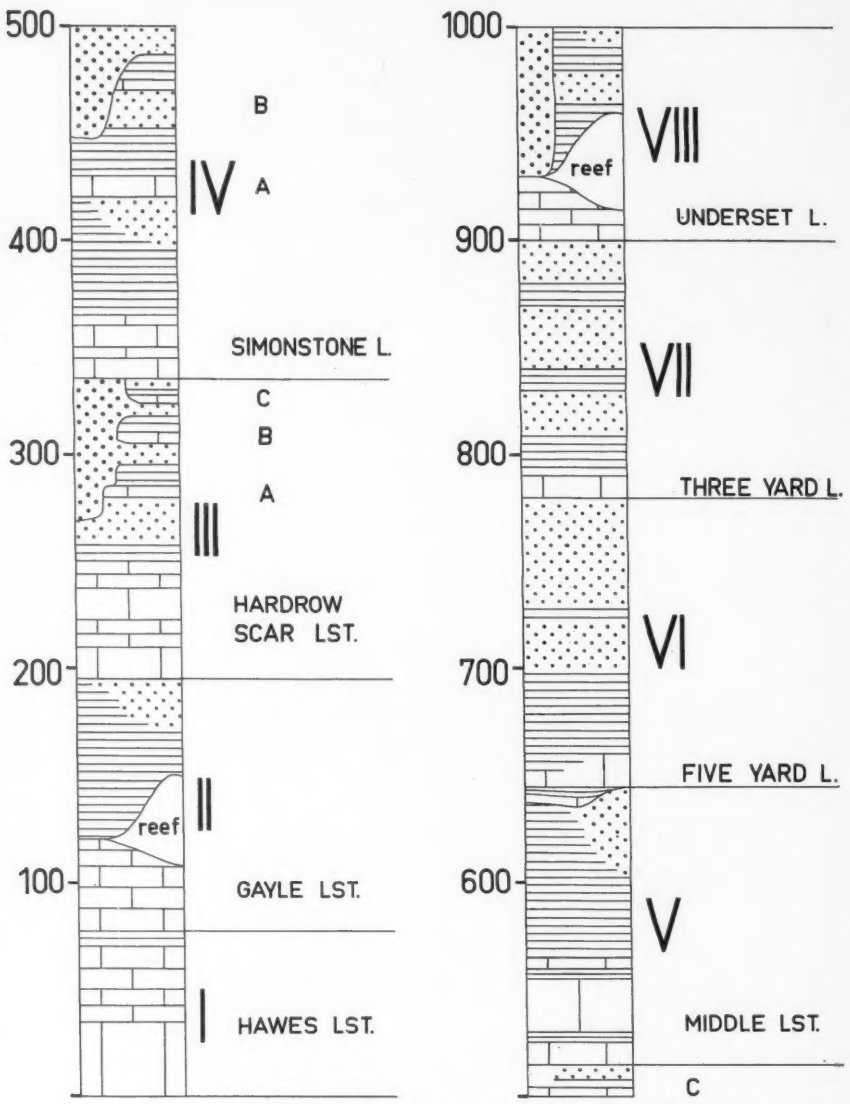

FIG. 2.—Type-section of the Yoredale Series, somewhat idealized.

the cyclothem. Members 2 through 5 form the bulk of the clastic members of any cyclothem; their degree of persistence is inversely proportional to their grain-size. Shale is the most persist of all members of the cyclothem.

Sandstone Types

The overwhelming bulk of all Yoredale Series sandstones are sheet sandstones, comprising members 4 and 5 of the cyclothem. The sheet sandstones are usually thin, often less than 10 ft; only occasionally do they exceed 20 ft in thickness. The basal contact of the sheet sandstone is, almost without exception, gradational. Sandstone first appears as a few discontinuous lenses in the upper part of the siltstones. They increase in thickness and amount upward while the amount of siltstone decreases until the rock becomes a flaggy sandstone with siltstone intercalations. The passage from flaggy sandstone to massive sandstone is also gradational. In contrast, the upper contact of most sheet sandstones is abrupt. Often it carries evidence of reworking, in the form of seat-earth or calcareous sandstone.

The greater part of any sheet sandstone consists of flaggy sandstone. In many places this member is the only component of a particular sheet sandstone. The flaggy sandstones are of fine or very fine sand, often with an admixture of coarse quartz silt. Many of them are micaceous; in isolated cases the mica may constitute 20 percent of the rock. Generally mica is a typical constituent of the truly laminated sandstones which consist of thin sheets of quartz grains separated by laminae of mica shreds. The rock splits readily along the mica laminae, usually spaced at 1 mm intervals through the rock. These laminated sandstones are of extremely small grain-size; often it is difficult to decide whether they are siltstones or sandstones. The other type of flaggy sandstone is usually ripple-marked, coarser, much less micaceous, and parts along the rippled surface only. Associated with the rippled surfaces are small brachiopods as well as a large variety of animal tracks. The two types of flaggy sandstone grade imperceptibly into each other; it has been found impossible to separate them in the field, and therefore no attempt has been made to separate them in the ideal cyclothem.

A widespread minor constituent of flaggy sandstones is calcite. Detrital grains—shell fragments and crinoid ossicles—occur in many ripple-marked sandstones. Exceptionally they may be sufficiently abundant to be seen at outcrop, but usually they are detected only by microscopic investigation. Whole fossils occurring on bedding planes have already been mentioned; their full articulation and occurrence in growth position mark them as original inhabitants of the sand sheet.

Massive sandstone forms a lesser part of the sheet sandstones of the Yoredale Series. It lies without notable exception on flaggy sandstone but is inevitably less extensive. The rock is usually composed of fine-grained sandstone often with an admixture of medium sand; mica forms only a very small part of the rock. Many of the massive sandstones are cross-bedded, the amplitude of the cross-bedding being about 2 ft. In a small number of cases the tops of individual beds of massive sandstone are ripple-marked, but in contrast to the flaggy sandstone, the ripples are confined to a single outcrop. The change from flaggy sandstone to massive sandstone is gradational in both horizontal and vertical directions.

Other sorts of sandstone occur in the cyclothems of the Yoredale Series, but too infrequently to be considered typical members of the cyclothem. The most important are channel sandstones, which occur in two different sizes. The smaller rarely achieve 10 ft in depth and are confined to the sheet sandstone in which they occur. The infilling is fine to medium sand, cross-bedded with the amplitude of the cross-bedding equal to the depth of the channel. Scour marks may occur in the base of the channel. The larger channels are completely different. They are from 50 to 100 ft deep and often more than a mile wide; their infilling is coarse and very coarse sand, typically showing cross-bedding of low amplitude. Plant fossils of large size are common. The upper surface of this coarse sandstone is hummocky; patchy siltstones and sandy seat-earths occupy the hollows.

The other important minor sandstone types are modifications of the sheet sand-

stone. The more common is a calcareous sandstone formed by the re-working of the top of a massive sandstone and the incorporation of detrital calcite in the product. Such sandstones are invariably related to the presence of one or another of the limestones of the Yoredale Series and are not usually of any great extent. The other sandstone type, known to occur only twice in the type-area, is a massive calcareous sandstone having an abrupt basal and a gradational upper contact with the siltstones in which it occurs. The sandstone carries a fauna of brachiopods lying at all angles to the bedding. They are of the species which occur in growth positions on the ripple-marked surfaces of the flaggy sandstones. In neither case can this massive calcareous sandstone be traced to a connection with other sandstones in the cyclothem.

DEPOSITIONAL ENVIRONMENT

Earlier work by the writer (Moore, 1958; 1959) has established close comparisons between the sediments of the Yoredale Series and those of the Mississippi Delta (Russell & Russell, 1939; Fisk and others, 1954; Fisk & McFarlan, 1955). The resemblance of the large-sized channels of the Yoredale Series to the channels of the shoal-water deltas of the Mississippi delta-complex invite comparison between the older parts of the modern delta and the Carboniferous cyclothems.

The Yoredale Series delta-complex shows increase in amount of clastic sediments when traced from the type-area northwards into Northumberland (Moore, 1959). In this direction also the limestone members thin and die out. One may conclude from this evidence that the delta-complex had its apex to the north and spread out southward. Accordingly, the regional slope must have been to the south. Potter & Siever (1956), working on rocks of similar age and environment, have shown that the mean direction of cross-bedding coincides with the direction of regional slope. It is to be expected, therefore, that the cross-bedding in the Yoredale Series would show a dominance of southerly dips. How nearly this approaches the truth is a measure of the influence of the regional slope on the carrying currents. Where there is clear divergence from this southerly direction of flow, a control other than regional dip must be operating.

SEDIMENTATION UNITS IN SANDSTONES

It cannot be stressed too strongly that the four main clastic members of the Yoredale Series cyclothem grade into one another. Abrupt contacts outside channel sandstones are the exception. The gradation, most clearly visible vertically, is also present horizontally. In fact, at the edge of a particular delta-complex it is possible to map the distribution of the four clastic members. Figure 3 illustrates the clearest examples of this; in figure 3A the boundaries are simple, a reflection of the essentially simple vertical succession in this cyclothem; in contrast, figure 3B shows a more complex relation. In this cyclo-

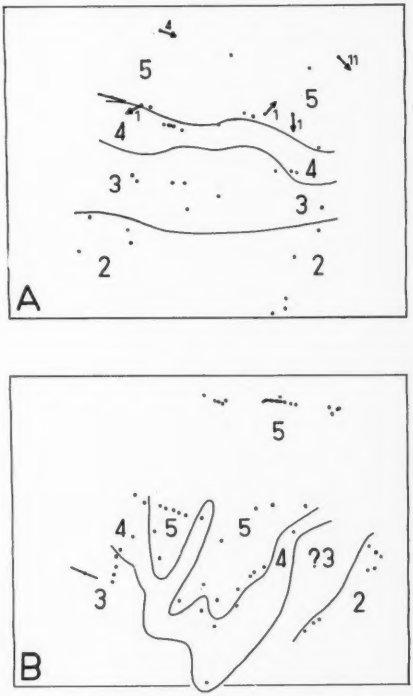

FIG. 3.—Areal distribution of clastic members of cyclothems. A—Cyclothem V; B—Cyclothem II.

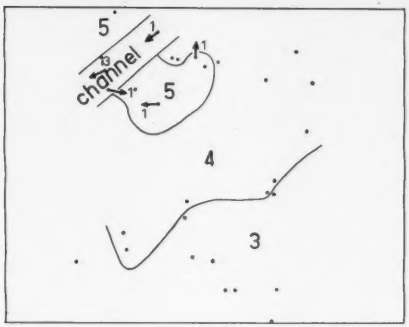

FIG. 4.—Areal distribution of sandstone members of Cyclothem VII.

them the succession in the most northerly outcrops comprises four or more repetitions of the clastic members whereas in the southerly outcrops that show sandstone there is invariably a single cycle. Still greater complexity is introduced by the inclusion of a channel sandstone. At its simplest the result is as shown in figure 4. The evidence of the scanty foreset dips in this sandstone suggest that the tongue of massive sandstone was derived from the channel.

Perhaps the clearest case of derivation of massive sandstone tongues from channel sandstones occurs in Cyclothem IV (fig. 5). In this complex major cyclothem Sandstone 2 contains both a channel phase and a sheet phase. Two tongues of massive sandstone cap the sheet phase, one of them being clearly derived from a bend in the channel. The southern tongue, of which only one margin is known, is interesting in that it contains a fine example of change of current-direction during deposition of a sandstone unit. In the outcrop where this is seen, cross-bedding at the base of the massive sandstone dips at 049°, 050°, 066°, and 066°, the mean direction being 056°. Four ft above this group of foresets is another, the dips being 305°, 310°, and 322°, with a mean at 312°. Here without doubt the depositing current changed its direction during deposition. Both directions are shown on the map (fig. 5).

The tongues of massive sandstone illustrated so far have all been of small size, but much larger ones occur. The largest known at present extends for well over 100 square miles; its known extent is shown in figure 6, where it can be seen that the bed was deposited *up the regional slope.*

Sheet Sandstones with Multiple Tongues of Massive Sand

One example of a sheet sandstone with more than one tongue of massive sandstone has already been illustrated (fig. 5). Figure 6 also suggests the presence of more than one tongue of massive sand. In both these cases the direction of current flow is the same in each tongue in a particular sheet sandstone. Very different conditions are implied by the sandstone shown in figure 7 where the

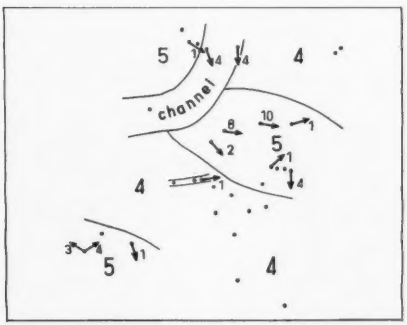

FIG. 5.—Derivation of sheet sandstones from channel sandstone in Cyclothem IV

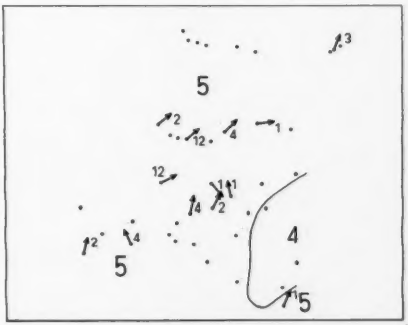

FIG. 6.—Largest mapped tongue of massive sandstone.

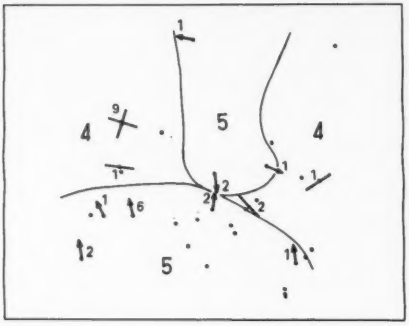

FIG. 7.—Sheet sandstone with multiple tongues of massive sandstone, Cyclothem III.

tongues of massive sandstone have opposed directions of flow. If these tongues were derived from channels, it seems more likely that they were contributed from two different channels rather than widely separated points on the one channel.

The two tongues of massive sandstone appear, from the evidence shown in figure 7, to impinge upon one another. The point of impingement is not exposed so that the relative age of the two tongues cannot be ascertained directly. Indirect evidence is found in the most westerly outcrop of the flaggy sandstones which comprises 20 ft of ripple-marked sandstone. The orientations of ripple marks measured at this outcrop were as listed in table 1.

TABLE 1.—*Orientations of ripple marks in Cyclothem III*

Depth below top of sandstone in feet	Elongation of ripple-marks
5	074°
10	128°
10½	031°
11	039°
11½	034°
14½	045°
15	077°
16½	107°
17½	057°

The intermixing of two sets of ripple-marks grouped around 100° and 035° suggests that currents from both tongues of massive sandstone were involved simultaneously, and therefore the tonques were contemporaneous.

LOCAL RELIEF ON THE DELTA

Depositional relief over the delta-front is, naturally, the most pronounced. A part of the delta-front of Cyclothem V is shown in figure 3A where the presence of patchy seat-earth in the northwest outcrops indicates emergence and the 5 ft of calcareous shale in the southeast clearly imply continuous marine conditions. The present thickness difference between the two sections is 145 ft, which may safely be increased to 200 ft by removing the effects of compaction in the shales and siltstones. This particular delta, therefore, was deposited in water some 200 ft deep, the gradient on the delta-front being about 20 ft/mi.

Relief within the delta-complex was naturally much less than 200 ft, but only rarely can the exact figure be estimated. Broadly speaking, relief may be divided into two phases—before and after sand-deposition. There is abundant evidence that sand sheets radically altered the local relief. Two instances of pre-sandstone relief are worth describing. The first occurs in Cyclothem III where in the type area a fourth minor cyclothem is developed over only a part of the area mapped. At the feather edge of this minor cyclothem the basal limestone passes laterally into a calcareous sandstone directly overlain by the basal beds of the succeeding major cyclothem. The calcareous sandstone marks the old shoreline. Some miles to the north the minor cyclothem is fully developed to the extent of having a seat-earth developed on top of the massive sandstone. The thickness of the minor cyclothem at this place is 10 ft, suggesting an original depth of at least this amount at the time the sand was being deposited. The details appear in figure 8.

A second instance of pre-sandstone relief occurs in Cyclothem IV. In member 3 of the lowest minor cyclothem there is found a sandstone intercalation which shows graded bedding. No sole markings are known, but the distribution of the bed (fig. 9) indicates a derivation from the southwest.[2] This is approximately the direction of

[2] Since completing the manuscript, Hicks (1959) has reported the presence of slumping in the identical horizon on Inglebrough. The outcrop, apparently the only one on Inglebrough at this horizon, occurs two miles due south of the southwest corner of figure 9. (Hicks, P. F., 1959)

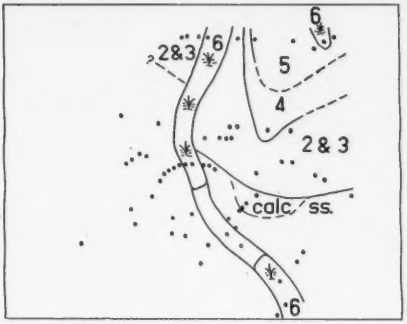

FIG. 8.—Minor cyclothem IV (4) and contemporaneous deposits.

current-flow in the succeeding sheet sandstone illustrated in figure 6. The persistence of direction of current-flow in this minor cyclothem indicates that an 8-ft bed of graded sand was insufficient to affect local relief.

Post-sandstone relief can also be demonstrated. Sandstone IV (2), already described in figure 5, consists of two very distinct tongues of massive sandstone resting on a continuous sheet of flaggy sandstone. Both tongues of massive sandstone are capped in part by seat-earth, indicating emergence. The seat-earths are in turn overlain by a thin limestone which is sandy in contact with the seat-earths. In the better-known patch of sandy limestone, the bed is only 4 in thick at outcrop, and it is quite possible that it died out completely to the north. Renewal of clastic deposition brought to an end this local relief, as the succeeding sheet sandstone is completely unaffected by it. Figure 10 illustrates the successive stages of formation, modification, and burial of this relief.

SUMMARY OF CONDITIONS

The foregoing evidence shows that the sheet sandstones of the Yoredale Series were derived from channel sandstones, some of which (in Cyclothems III and IV) gave rise to two super-posed series of sheet sandstones. In the initial stages of deposition of a sheet sandstone a channel is flanked by shallow depressions. In the absence of clastic sedimentation, lime-mud accumulates in these depressions. Deposition from the channel halts lime-deposition as it initiates clastic sedimentation, building out a tongue of massive sandstone. Cross-bedding is a typical feature of the tongue of massive sandstone, and is disposed radially. Laterally the massive sandstone passes outwards into flaggy sandstone and still further from the point of origin of the sheet, it passes into siltstones. Near the point of origin the sheet sandstone may lie very close to the limestone and be mostly massive. Farther out the proportion of massive sandstone decreases as the flaggy sandstone and siltstone thicken.

Each sheet sandstone consists of a number of tongues of massive sandstone not necessarily deposited from the one channel. The tongues vary in size and direction of growth from the channel. In one sheet sandstone there is little doubt that two channels contributed.

Temporary relief in the channel-flank depressions both before and after sandstone deposition can be adduced, in the latter case sufficiently pronounced to cause emergence of the top of the sheet sandstone and its consequent colonization by plants.

Conditions very similar to those described have been found in the Mississippi delta. Russell & Russell (1939) describe how infilling of inter-distributary hollows results from crevassing in the levee-bank of a confining channel. They show that the crevassing occurs because of overtopping of the bank during floods and that deposition takes place in the hollow because of a favorable gradient compared with the channel. The

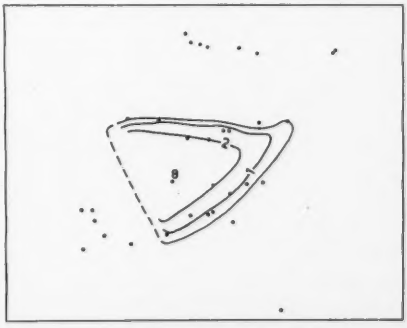

FIG. 9.—Extent of graded-bedded sandstone in Cyclothem IV.

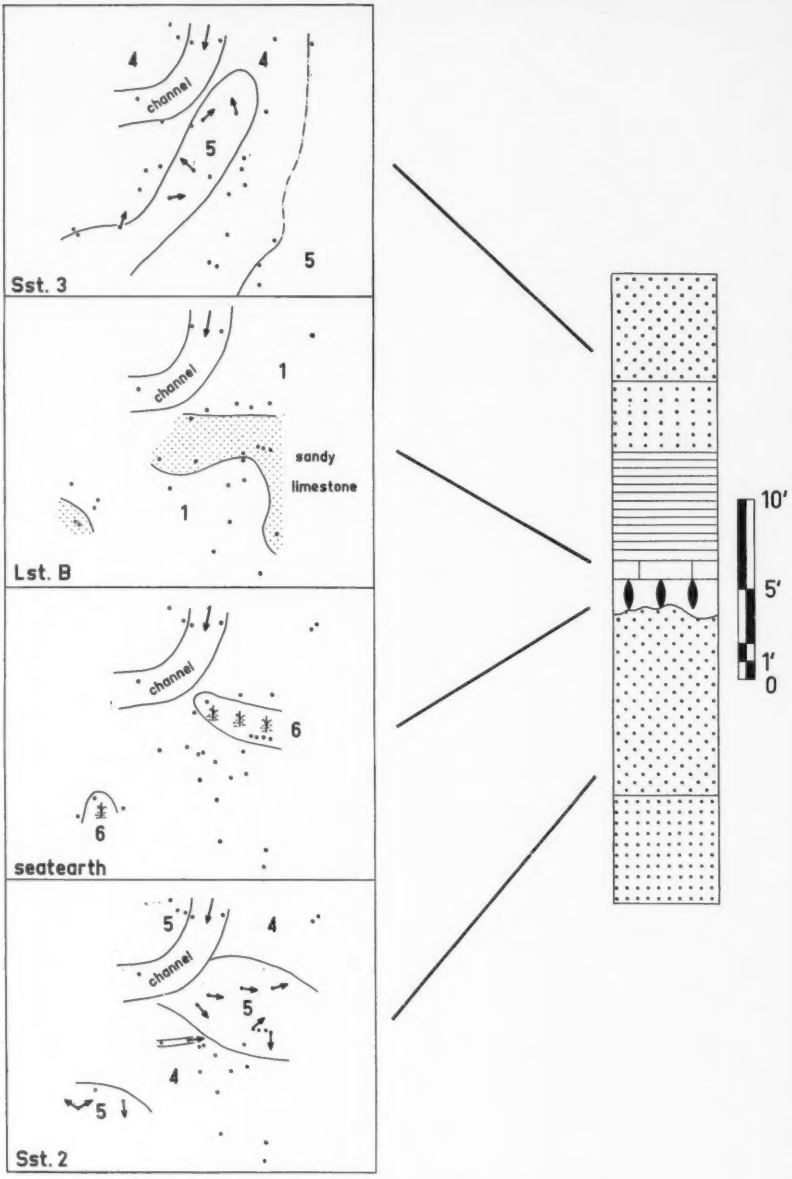

FIG. 10.—History of emergent tongue of massive sandstone in Cyclothem IV.

duration of a crevasse is governed by the persistence of this gradient, the angle of divergence from the channel, and the possibility of fortuitous blocking of the crevasse by floating vegetation becoming stranded in its mouth. The only other control on the size of the wedge of sediment deposited in a hollow is the size of the hollow itself.

CONCLUSIONS

Sheet sandstones in the cyclothems of the Yoredale Series are derived from channels by multiple crevassing of the banks of distributary channels. Each sheet sandstone consists of a series of tongues of massive sandstone linked together by their fringes of flaggy sandstone. The bulk of any sheet sandstone consists of flaggy sandstone; the massive sandstone tongues are much less extensive. Cross-bedding in the massive sandstone tends to have a radial distribution in each tongue. The form of the tongue is controlled by pre-existing local relief; a slightly older tongue close at hand, the angle of divergence of the crevasse from the channel, and the shape of the hollow in which deposition occurs all play their part.

The surface of a sheet sandstone often shows local relief. Much of the tongue of massive sandstone appears to be emergent sufficiently for it to be colonized by plants, and this relief persists until the renewal of clastic deposition in the succeeding minor cyclothem.

The purely local nature of the tongues of crossbedded sandstone and the radial distribution of cross-bedding in the tongues render them useless for studies of regional gradient such as those carried out by Potter and Siever (1956) on the Pennsylvanian of the central United States. On the other hand they may be used to reconstruct the form of the delta surface with great accuracy, leading to a better understanding of the conditions of deposition of the sheet sandstones and the mode of formation of these particular cyclothems.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 30, NO. 2, PP. 228–240
FIGS. 1–5, JUNE, 1960

THE BASAL CHEPULTEPEC SANDSTONE (CAMBRIAN-ORDOVICIAN BOUNDARY) IN THE RIDGE AND VALLEY PROVINCE OF TENNESSEE[1]

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ABSTRACT

Examination of the well-sorted quartzose sandstone indicates a decrease in grain size as well as a diminution of heavy minerals to the east and southeast. Characteristic heavy mineral suites from the three fundamental types of source rock occur in the sandstone. Their areal distribution suggests a provenance to the north and northwest.

INTRODUCTION

The boundary of the Cambrian-Ordovician Systems in the Ridge and Valley province in Tennessee has been established below the thickest and most prominent sandstone bed (where several occur) of the Chepultepec Dolomite (Ordovician) but above the highest of the characteristic coarsely oolitic chert layers of the Cooper Ridge Dolomite (Cambrian) in the northwest phase of the Knox Group. The same lithologic criterion is used in the southeast phase where the Cambrian and Ordovician equivalents are the Conococheague Limestone and the Jonesboro Limestone (Rodgers, 1953). The distribution and equivalents of the Knox Group may be seen in figure 1.

A conformable relationship exists between the Cambrian and Ordovician Systems in the Ridge and Valley of Tennessee. Thus, the boundary is not marked by a depositional hiatus.

Prior to the deposition of the Knox Group, the detritus was brought into the geosyncline from the northwest—the area of the craton. Post-Knox detritus was derived from the east—the area of the island arcs. This problem is concerned with the source of the basal Chepultepec sandstone and which provenance is reflected therein.

Previous Investigations

Prouty (1938) studied the Chepultepec sandstone beds at Norris, Tennessee. A similar study was undertaken by Nicholas (1956) in Virginia. No previous study has been made of the sandstone throughout the Ridge and Valley in Tennessee

DEPOSITIONAL ASSOCIATION AND SIGNIFICANCE OF THE BASAL CHEPULTEPEC SANDSTONE

According to Pettijohn (1957, p. 611, 612), the sandstone-carbonate relationship appears to be a consanguineous association.

Throughout the Ridge and Valley, the Knox Group can be traced to Pennsylvania and New York. In Kentucky and central Tennessee the base of the Knox has been penetrated by drill holes. Apparently, there are no dolomite equivalents of the Knox in Ohio, Illinois, and Indiana.

So far as is known, the broad landmass west of the Appalachian geosyncline was nowhere submerged by the sea during Early or Middle Cambrian times (Moore, 1949). During the latter part of the Cambrian Period, the sea apparently encroached upon parts of the craton. Schuchert (1955, maps 6, 7, 8) envisions the strand line as being "J" shaped. Perhaps the crook of the "J" was the extension of the Canadian shield. It would appear from Schuchert's figures that the nearest source of detrital material was to the north or to the east. At the close of the Cambrian Period, according to Moore (1949), the sea withdrew from most parts of the continent.

In the writer's opinion, the withdrawal of the sea from the craton may be indicated by the basal Chepultepec Sandstone. It may have been deposited under conditions as described below.

[1] Manuscript received July 29, 1960.
[2] This study was carried out while the author was associated with the University of Tennessee.

			NORTHWEST PHASE	SOUTHEAST PHASE
			Unconformity	
Ord.	L	Knox Group	Mascot Dolomite / Kingsport Formation } Newala Formation	Jonesboro Limestone
			Longview Dolomite	
			Chepultepec Dolomite	
Camb.	U		Copper Ridge Dolomite	Conococheague Limestone

FIG. 1.—Generalized stratigraphic section of the Knox Group in the Ridge and Valley Province in Tennessee.

A withdrawal of the sea would move the strand line in the direction of regression, subjecting the newly exposed land surface to the processes of sub-aerial erosion. Should this process continue, the exposed areas would be close enough to what is now east Tennessee to contribute sand-sized particles. In this area, relatively shallow seas persisted as evidenced by rain prints, cross-bedding, and ripple marks (both current and oscillation type) as bedding features of the sandstone. Littoral and neritic conditions probably prevailed during the deposition of the sand.

Transgression and regression probably accounts for the different layers of sandstone interbedded with carbonate rocks (Rodgers, 1953). An uplift of the source area could also account for the sands.

FIELD SAMPLING

Spot sampling was the method employed in obtaining samples for this study. By traversing numerous Knox belts, the sandstone was studied at the points indicated in figure 2. More exact locations of sampling sites are given in table 1. Road cuts, railroad cuts, and streams proved most advantageous for this purpose.

The thickness of the sandstone, its color,

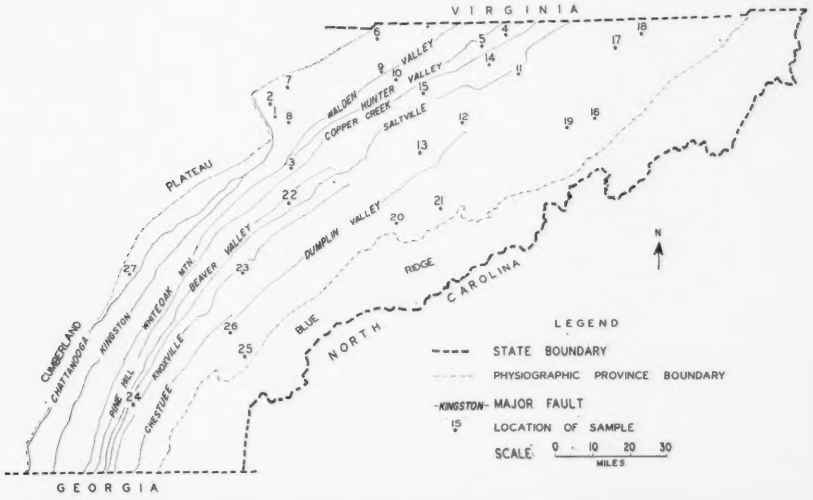

FIG. 2.—Location map showing the major faults in the Ridge and Valley Province in Tennessee.

TABLE 1.—*Sample locations*

Sample Number	T.V.A. Quadrangle	Grid[1]
1	Jacksboro	2,534,800 E:693,100 N
2	Jacksboro	2,527,900 E:697,050 N
3	Powell	2,556,950 E:607,250 N
4	Kyles Ford	2,870,100 E:800,070 N
5	Lee Valley	2,813,800 E:756,500 N
6	Middlesboro So.	2,679,850 E:781,300 N
7	Demory	2,559,900 E:717,450 N
8	Norris	2,570,000 E:668,600 N
9	Clouds	2,689,300 E:737,100 N
10	Tazewell	2,710,900 E:742,150 N
11	Pressmens Home	2,878,400 E:739,100 N
12	Bean Station	2,776,500 E:697,450 N
13	Joppa	2,735,400 E:647,100 N
14	Lee Valley	2,837,000 E:770,050 N
15	Avondale	2,755,350 E:729,000 N
16	Chuckey	2,989,700 E:687,000 N
17	Indian Springs	3,032,000 E:787,950 N
18	Indian Springs	3,029,550 E:819,450 N
19	Jearoldstown	2,965,350 E:713,450 N
20	Pigeon Forge	2,736,650 E:536,700 N
21	Clevenger	2,781,500 E:564,000 N
22	Lovell	2,539,800 E:577,300 N
23	Loudon	2,508,300 E:484,800 N
24	Charleston	2,364,650 E:318,550 N
25	Mount Vernon	2,505,500 E:363,250 N
26	Englewood	2,449,800 E:370,650 N
27	Spring City	2,350,100 E:484,600 N

[1] The grid system as used here is the 10,000-foot Tennessee co-ordinate established by the United States Coast and Geodetic Survey.

type of bedding, type of cement, surface and bedding features, degree of weathering, and its relation to overlying and underlying strata were recorded.

Samples from the top, middle, and base of the bed were taken at right angles to the bedding, and the position of each sample in relation to the base was recorded. This sampling procedure, in effect, gives a partial channel sample. As has been mentioned previously, several sandstone layers may exist in one location. Where only float occurred, no loose material was collected because of the uncertainty in determining the exact sandstone layer under study.

LABORATORY PROCEDURE

Samples from the top and bottom of the bed were used for most of the following analyses. The middle sample at each site was held in reserve in order that intermediate analyses might be made if required. In some instances, it was necessary to combine the entire series to obtain an adequate sample.

Preparation of Samples for Analysis

Three types of cement, dolomite, calcite, and silica, are present in the sandstone, and the procedure for the disaggregation of the grains was dependent on the type of cement (or lack of it) of the sample.

The samples with a calcite or dolomite cement were placed in a 500 ml Erlenmeyer flask and 200 ml of dilute hydrochloric acid (1:4) were added. Upon cessation of the effervescence, the liquid was siphoned off and fresh HCl was added. This process was continued until no effervescence was discernible. The action of the acid was sufficient to rid the sample of the carbonate cement. The sample was then washed several times with water.

Difficulty was encountered with those samples having a siliceous cement. No known chemical will dissolve the cement and at the same time leave the detrital quartz grains and other constituents of the rock unaltered. A relatively large quantity of slides would have had to be made in order

to derive any reliable data through thin section analysis which is recommended in such cases. The time and labor involved in such a procedure would have been prohibitive. Consequently, another method was sought. The surface of the sample was scraped with an aluminum knife to free the grains from the cement. Although this technique proved satisfactory, the paucity of grains acquired by this method made it necessary to combine the entire series of samples collected at certain localities. Some samples were so tightly cemented with silica that disaggregation was impossible. For this reason, samples 8, 10, 14, 17, 21, and 27 were not analyzed in the laboratory.

Where no cement was present, crushing without pressure with a rolling pin was employed. The weight of the rolling pin was sufficient to separate the grains.

Where the carbonate cement had been leached, most grains were coated with variable amounts of iron oxide, and for identification purposes it was necessary to remove the coating. This was accomplished by placing the grains in a flask to which dilute HCL (1:4) was added. The contents were brought to a boil for a period ranging from 10 to 30 minutes depending on the amount of iron oxide coating. The grains were then washed several times with water to remove the HCl and dissolved iron oxide.

Krumbein and Pettijohn (1938) state that some workers have maintained that apatite is destroyed by the reaction with hydrochloric acid, although Reed (1924) claims that the acid has no apparent effect. The writer's observations confirm those of Reed in regard to apatite.

Technique of Analysis

Sifting.—The same series of sieves was utilized in the sifting of the grains in order to have a standard for comparison. A series of U. S. Standard Sieves with the $\sqrt{2}$ scale was used, with mesh openings of 707, 500, 354, 250, 176, and 124 microns with a pan placed at the bottom to catch those grains finer than 124 microns in diameter.

The nest of sieves with the prepared sample poured into them was placed in a Ro-Tap shaker for 10 minutes. At the end of this time the quantity of grains retained on each sieve was weighed and the weights recorded. Subsequently, these weights were used to compute percentages needed for further statistical analysis. Histograms and cumulative frequency curves were drawn from the results obtained in this manner. The 25, 50, and 75 percent quartile values are given in table 2 as Q_1, Q_2, and Q_3 respectively.

Heavy mineral separation and identification.—The heavy mineral fraction was separated from the rest of the sample by the use of Tetrabromoethane (sp. gr. = 2.95 at 20° C.).

Both the binocular microscope and the petrographic microscope were employed in the identification of the heavy minerals and the light fraction.

RESULTS OF MECHANICAL ANALYSIS

By using the quartile values indicated in table 2, the Sorting (*So*), and the Size Distribution (*QDa*) may be determined.

Sorting

The values of sorting range from 1.13 to 1.48. A well-sorted sediment has a value of 2.5 or less according to Trask (Krumbein and Pettijohn, 1938, p. 282). Figure 3 shows the distribution of sorting at the locations indicated.

Size Distribution

The averaged size distribution values range from .0189 to .1066 mm. The distribution of sizes is represented in figure 4.

Conclusions

The conclusions presented below are based on figures 3, 4, and 5.

The distribution of the sorting coefficient (fig. 3) reveals no striking pattern from the data available.

The particle sizes (*QDa*) (fig. 4) become finer to the south and southeast. The significance of the increasing smaller sizes in that direction seems to indicate the source of the detritus was to the north and northwest.

In general, the sandstone appears to become increasingly thinner to the south; the thickest areas are in the northeast and northwest portions of the region discussed in this paper (fig. 5). The thickening of the sandstone in the northern regions could be due to irregularities on the sea floor.

TABLE 2.—*Comprehensive results of mechanical analysis*

Sample Number	Mm			$So=\sqrt{\frac{Q_1}{Q_2}}$	Aver.	$QDa=\frac{Q_1-Q_2}{2}$	Aver.
	Q_1	Q_2	Q_3				
1a	.3121	.2588	.2415	1.13	1.16	.0353	.0401
1c	.2871	.2500	.1975	1.20		.0449	
2a	.3789	.3368	.2973	1.12	1.17	.0408	.0498
2c	.3511	.2872	.2333	1.22		.0589	
3	.4353	.3299	.2222	1.39	1.39	.1066	.1066
4	.3078	.2500	.1921	1.26	1.26	.0578	.0578
5a	.2774	.2333	.1895	1.21	1.26	.0440	.0542
5c	.3078	.2382	.1792	1.31		.0643	
6a	.2535	.2017	.1528	1.28	1.31	.0504	.0538
6c	.2483	.1895	.1350	1.35		.0572	
7a	.3511	.2813	.2120	1.28	1.27	.0696	.0696
7c	.3536	.2872	.2146	1.26		.0695	
9a	.2643	.1894	.1528	1.31	1.42	.0558	.0672
9c	.2736	.1731	.1166	1.53		.0785	
11a	.2500	.2031	.1528	1.26	1.26	.0486	.0493
11c	.2717	.2333	.1719	1.26		.0499	
12a	.3511	.2500	.1684	1.44	1.48	.0913	.0891
12c	.3078	.2161	.1340	1.52		.0869	
13a	.3299	.2333	.1768	1.33	1.23	.0766	.0748
13c	.3729	.2872	.2269	1.13		.0730	
15	.2852	.2300	.1768	1.27	1.27	.0542	.0542
16	.3463	.2738	.1921	1.34	1.34	.0771	.0771
18a	.3253	.2500	.2031	1.27	1.28	.0611	.0567
18c	.2679	.2073	.1634	1.28		.0523	
19	.2379	.2176	.2102	1.15	1.15	.0189	.0189
20a	.5359	.5000	.4353	1.11	1.38	.0503	.0722
20c	.3078	.1719	.1199	1.65		.0940	
22	.3078	.2994	.2415	1.13	1.13	.0332	.0332

Samples 8, 10, 14, 17, 21, and 27 could not be disaggregated in order to obtain data.
"a" refers to upper sample at location.
"c" refers to lower sample at location.
Where no letter occurs, the entire sample was combined for data.

TABLE 2.—*Continued*

Sample Number	Mm			$So = \sqrt{\frac{Q_1}{Q_2}}$	Aver.	$QDa = \frac{Q_1 - Q_3}{2}$	Aver.
	Q_1	Q_2	Q_3				
23a	.4061	.3078	.2382	1.31	1.38	.0840	.0889
23c	.3539	.2349	.1661	1.46		.0938	
24a	.2031	.1649	.1460	1.18	1.29	.0286	.0452
24c	.2500	.1768	.1267	1.40		.0617	
25a	.2176	.1649	.1250	1.33	1.29	.0461	.0390
25c	.2176	.1768	.1518	1.20		.0329	
26a	.2349	.1649	.1250	1.37	1.30	.0550	.0496
26c	.2500	.2031	.1638	1.23		.0431	

Although no statistical study of the roundness of quartz grains was made, it was noted, that they showed a noticeable increase in roundness to the south and southeast.

RESULTS OF MINERAL IDENTIFICATION

The basal Chepultepec Sandstone has a marked paucity of heavy minerals. There is less than .01 percent of this fraction by weight.

Identification and Description

The minerals identified for each sample may be seen in table 3. A detailed description of the minerals identified by the writer is tabulated in table 3. The heavy minerals (including authigenic grains) are listed be-

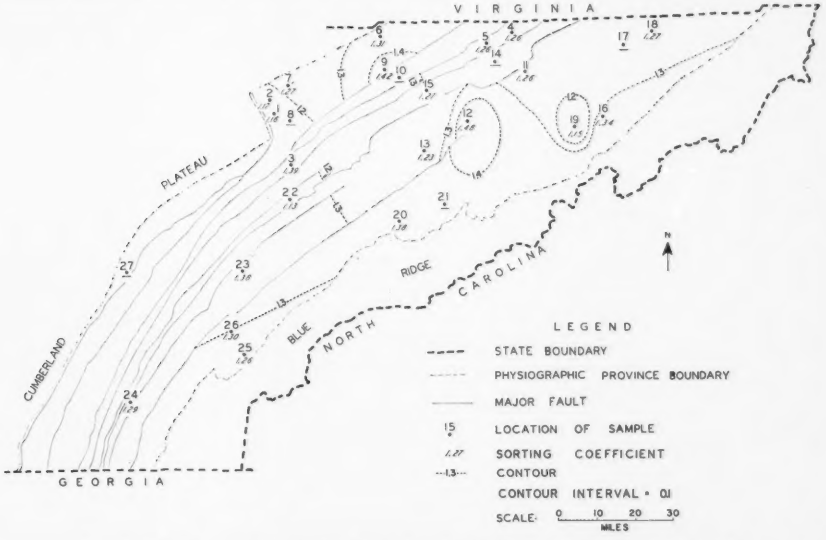

FIG. 3.—Sorting coefficient map of the basal Chepultepec Sandstone in the Ridge and Valley Province in Tennessee.

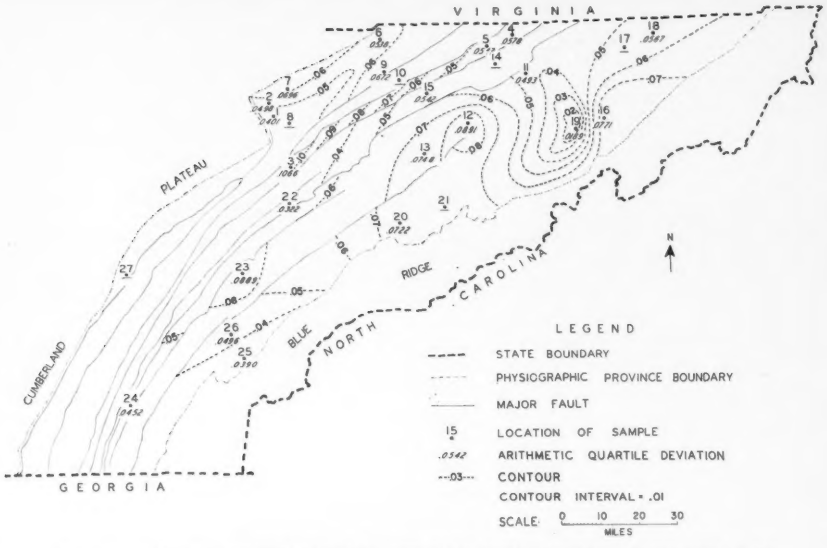

FIG. 4.—Arithmetic quartile deviation map of the basal Chepultepec Sandstone in the Ridge and Valley Province in Tennessee.

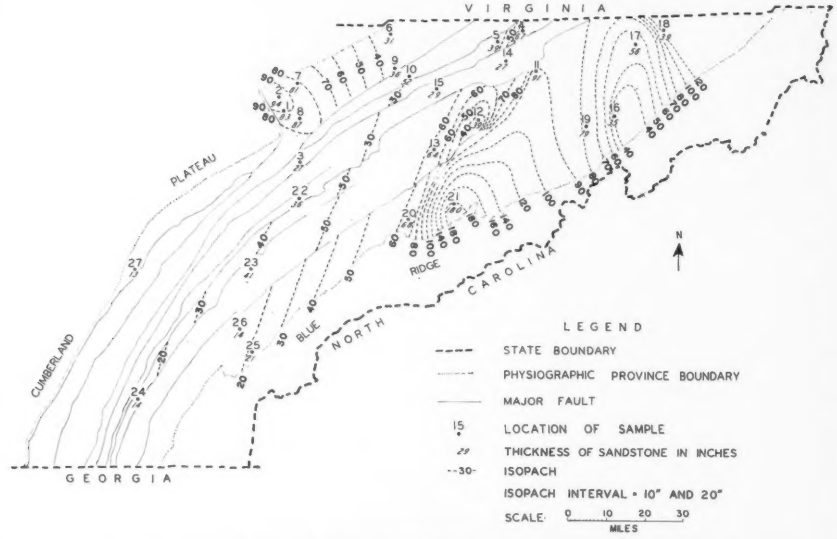

FIG. 5.—Isopach map of the basal Chepultepec Sandstone in the Ridge and Valley Province in Tennessee.

TABLE 3.—*Minerals identified in the basal Chepultepec Sandstone*

Minerals	Indices	Description
Heavy fraction		
Actinolite-Tremolite	$n\alpha = 1.60–1.61$ $n\gamma = 1.62–1.64$	colorless to pale green; fibrous, prismatic, elongate; extinction 10°–17°; 2V approx. 80° (−); length slow.
Anatase	$n\epsilon = >1.80$ $n\omega = >1.80$	blue (pleochroic), yellow; sub-angular, uniaxial (−); some grains with inclusions.
Apatate	$n\epsilon = 1.63$ $n\omega = 1.65$	light green; rounded; uniaxial (−).
Cassiterite	$n\epsilon = >1.80$ $n\omega = >1.80$	colorless with brown overcast, reddish; subangular; conchoidal fracture; uniaxial (+); some grains with inclusions.
Dumortierite	$n\alpha = 1\ 66$ $n\gamma = 1.68$	pink (weak pleochroism); fibrous; parallel extinction; moderate 2V (−); length fast.
Epidote	$n\alpha = 1.72$ $n\gamma = 1.75$	pistachio green (very weak pleochroism); subrounded; equidimensional; 2V very large (−).
Fluorite	$n = 1.43 > 1.44$	blue; subangular-subrounded; isotropic; some grains twinned.
Garnet	$n = 1.79$	red; subangular-subrounded; conchoidal fracture; isotropic.
Hornblende	$n\alpha = 1.66$ $n\gamma = 1.70$	brown (pleochroism); rounded, some have prismatic form; oblique extinction; 2V fairly large.
Periclase	$n = 1.73 > 1.74$	light blue; euhedral to subangular; cubic cleavage; isotropic; some grains with inclusions; vitreous luster.
Rutile	$n\epsilon = >1.80$ $n\omega = >1.80$	red; translucent; angular to rounded; optical properties masked; well formed crystals, some with geniculate twins.
Sillimanite	$n\alpha = 1.66$ $n\gamma = 1.68$	brown (weak pleochroism); fibrous; parallel extinction; 2V approx. 20° (+); length slow.
Sphene	$n\alpha = >1.80$ $n\gamma = >1.80$	colorless, brown (pleochroism); some euhedral (diamond-shape), some subangular; extinction not complete; strong dispersion $r > v$; 2V approx. 30° (+).
Topaz	$n\alpha = 1.61$ $n\gamma = 1.62$	colorless; subangular; irregular fracture; 2V approx. 60° (+).
Tourmaline	$n\epsilon = 1.62$ $n\omega = 1.66$	black, blue, brown, green (pleochroism); euhedral to well rounded; fragmental, elongate, equidimensional; parallel extinction; uniaxial (−); length fast; secondary overgrowths, some in almost exact optical continuity with the nucleus.
Zircon	$n\epsilon = >1.80$ $n\omega = >1.80$	colorless, pink; rounded, rod shaped, equidimensional—some with crystal faces (authigenic ?); parallel extinction; uniaxial (−); length slow.
Zoisite	$n\alpha = 1.70$ $n\gamma = 1.71–1.72$	colorless; perfect cleavage; parallel extinction; 2V approx. 10° (+); some grains with inclusions.
Light fraction		
Chert (detrital)		white; rounded; dull luster; mosaic appearance in crossed nicols.
Feldspar		white, tan; dull luster (poss. due to kaolinization); secondary enlargement (the composition of which is shown in parentheses); nuclei are rounded as well as rod and sphere shaped.
Microcline (microcline)	$n\alpha = 1.52$ $n\gamma = 1.53$	
Albite (albite)	$n\alpha = 1.52$ $n\gamma = 1.53$	

(*Continued on next page*)

TABLE 3.—*Continued*

Minerals	Indices	Description
Albite-Oligocl. (albite)	$n\alpha = 1.53$ $n\gamma = 1.54$	
Muscovite	$n\alpha = 1.57$ $n\gamma = 1.59$	colorless; thin, transparent sheets; edges slightly rounded to subangular; 2V approx. 40° (−).
Quartz	$n\epsilon = 1.55$ $n\omega = 1.54$	clear, milky, rose, smokey; rounded-subangular; uniaxial (+); pitted surface (possibly due to corrosion by cement)
Glauconite		black, dark green; botryoidal; alters to limonite.
Opaque minerals		
Hematite (authigenic)		red; several grains botryoidal; earthy aggregations.
Ilmenite		black with purplish tinge; subangular to subrounded; slightly magnetic; some alteration to leucoxene.
Leucoxene		white, tannish white; rounded to subrounded; dull luster
Limonite (authigenic)		yellow, orange, brown; earthy aggregates; pseudomorphs of glauconite and pyrite.
Magnetite		blue-black; subrounded to subangular; magnetic.
Pyrite		brass-yellow; irregular aggregates, partial cubes; alters to limonite.

low in the order of their abundance on a regional basis: tourmaline, zircon, rutile, limonite, pyrite, magnetite, leucoxene, actinolite-tremolite, garnet, hematite, hornblend, anatase, ilmenite, fluorite, dumortierite, epidote, sphene, periclase, cassiterite, sillimanite, apatite, topaz, zoisite. The light minerals listed below in order of abundance are quartz, detrital chert, feldspar, muscovite, glauconite.

Conclusions

The basal Chepultepec Sandstone may properly be classified as an orthoquartzite (as defined by Pettijohn, 1957, p. 291, 295–300) or a quartzose sandstone. It exhibits excellent sorting, well-rounded sand grains, cross-bedding, and ripple marks. The association with carbonate rocks and great areal extent compared to vertical extent are also typical of orthoquartzites.

Origin and Geologic Significance

The excellent sorting and rounding of the grains together with the high percentage of quartz is indicative of mineralogical maturity of the sandstone. Apparently it represents the final stage of a long period of weathering, sorting, and abrasion. The maturity of the sandstone suggested above may have been achieved in one of three ways: (1) the site of deposition and the source area remained tectonically stable; (2) the sand passed through at least two cycles of sedimentation; or (3) a combination of the previous conditions.

Concerning the first possibility, a consistent winnowing of the detrital material could produce the texture and structures described above. A first cycle orthoquartzite might be developed under a transgressive sea. Where the basement rock is near or locally where "monadnocks" of igneous or metamorphic rocks are present, characteristic heavy mineral suites of those rocks would be introduced.

The reworking of previously deposited detrital material would produce a higher degree of maturity. Thus, a second cycle sand might have characteristics similar to those produced under the stable conditions of the first suggestion.

As is shown by the data in table 4, the basal Chepultepec Sandstone contains representative minerals derived from all fundamental rock types; igneous, metamorphic, and sedimentary. All samples examined contained minerals of reworked sediments. It would appear, as is formulated below, that the sandstone was brought about by a combination of the first and second possibilities cited above.

Lighologic Conditions of the Craton

Some heavy detrital minerals identifiable in the basal Chepultepec Sandstone can be definitely categorized as having been derived from a pre-existing sediment. Minerals

TABLE 4.—*Relationship of heavy minerals to source rocks*

Minerals	Acid Ign. & Peg.	Basic Ign.	Metam.	Authigenic
Actinolite-Tremolite	R		C	
Anatase	R	F	R	F
Apatite	C	C	C	
Cassiterite	R			
Dumortierite	F		F	
Epidote		F	C	
Fluorite	F		R	
Garnet	F	R	C	
Hematite		all weathered rocks		C
Hornblende	A	F	A	
Ilmenite	R	A	F	
Leucoxene				C
Limonite		all weathered rocks		C
Magnetite	F	C	A	
Periclase	R	R	R	
Pyrite	C	R	C	A
Rutile	F	F	F	F
Sillimanite	R		A	
Sphene	C		C	R
Topaz	F		R	
Tourmaline	A		C	F
Zircon	C		R	
Zoisite			R	

Explanation: A = abundant occurrence; C = common occurrence; F = frequent occurrence; R = rare occurrence. *Data compiled from:* Dana (1946), Milner (1954), Pettijohn (1957), Wahlstrom (1955).

with worn overgrowths and rounded chert support this conclusion. Aside from such obviously reworked minerals, actinolite-tremolite, cassiterite and other minerals provide suggestions as to the nature of the rocks on the continent.

Other than the definitely identifiable sedimentary minerals, three distinct types of mineral suites diagnostic of source rocks are discernible. These are basic igneous, acid igneous and pegmatite, and metamorphic (table 4).

Abraded grains of anatase indicates a basic igneous source rock. Acid igneous and pegmatite source rocks are represented by euhedral, dark brown tourmaline (Krynine, 1946), igneous type hornblende, cassiterite, fluorite, and topaz. Metamorphic terrain is indicated by actinolite, epidote, sillimanite, and zoisite. Some minerals such as dumortierite could indicate either a pegmatitic or metamorphic environment.

Tremolite-actinolite seems to be related to a nearby source. This "mineral" is remarkably fresh, and therefore could not have been exposed to prolonged transport without marked abrasion because of its relative ease of wear. Other minerals (euhedral sphene, euthedral tourmaline, fresh hornblende) are also indicative of a nearby source.

The roundness of the grains increases to the south and southeast. There is a paucity of such minerals as actinolite-tremolite, euhedral tourmaline, and hornblende to the south and southeast. In the latter direction reworked sediments become more prominent also. The mathematical increase in reworked sediments could be due, however, to the decrease in that direction of minerals from other source rocks. The increase in the rounding of the grains and the decrease in the amount of heavy minerals (table 5) to the southeast could be attributed to a greater distance of transport in that direction.

A lack of new minerals to the southeast may be interpreted to indicate that the island arcs themselves probably did not contribute a marked amount of detritus to the geosyncline in this region at that particular time. It appears, therefore, that new detrital material may have come from the north and northwest during the latter part of the Cambrian Period and the beginning of the Ordovician Period. The source of detritus probably was from the craton—perhaps the extension of the Canadian Shield.

SUMMARY AND CONCLUSIONS

The purpose of this study was to determine the mineral composition and provenance of the basal Chepultepec Sandstone which marks the Cambro-Ordovician boundary in the Ridge and Valley province in Tennessee.

Standard field methods and analytical procedures were employed in the compilation of data upon which this study is based. Supporting field evidence was added to laboratory results where possible.

The deposition of the sand could be attributed to a minor regression of the Cambro-Ordovician sea or an uplift of the source area.

The sandstone is best classified as an orthoquartzite as determined by textural and structural features. It is well sorted. The size distribution (*QDa*) reveals a general trend of smaller sized grains to south and southeast.

Characteristic mineral suites from the three fundamental types of source rocks occur in the sandstone. The areal distribution of the heavy mineral suites of the source rocks suggest that the provenance was to the north and northwest. Evidently, no marked amount of new detritus was brought in from the southeast.

The writer believes that further work along the lines set forth in this paper is warranted. The collection of samples in locations between those chosen by the writer and the data derived from them should aid in a better understanding of the sedimentary conditions which prevailed.

ACKNOWLEDGMENTS

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TABLE 5.—*Mineral distribution and frequency*

Mineral	Northwest Phase															Southeast Phase					
	Location Number															Location Number					
	1	2	3	4	5	6	7	9	11	12	13	15	22	23	24	16	18	19	20	25	26
	132	211	86	79	170	93	181	108	71	48	35	28	18	37	51	32	61	57	21	40	31[1]
Heavy fraction Actinolite-Tremolite	R	F	R	F	R	F	S	R								R					
Anatase	C	F	R	C		F	F	R													
Apatite														R		R		R			
Cassiterite					R																
Dumortierite												R				R	R				
Epidote		R		R			R														
Fluorite		R		R		R			R						R			R			
Garnet	F					F	R	R	S	R	R	R				R	R			R	S
Hematite	S	F	A	C	R	R			R	R	R				R	R		R	R	R	S
Hornblende			R			S	S								R	R	R	F			
Ilmenite	R	R	R			R		R													
Leucoxene	F	F	R		S	R	S	C	R	S	S					F	F				
Limonite[2]	C	C	C	C	C	C	C	C	F	F	S				C	C	C	F	C	C	S
Magnetite	S	R	R	S	R	R	R	S	F	F	R		A	C	F	R	R	S	S	R	A
Periclase								S		R						R		R			
Pyrite	F	S	S	R	S		R	R	F	S	A	A		R	S	F	C	S	S	R	
Rutile	S	F	S	F	F	S	F	R	S	R	S	R	F	F	C	R	R	R	R	S	R
Sillimanite														S	R						
Sphene						R								F		R					
Topaz					R																
Tourmaline	C	A	C	A	C	C	C	A	A	A	A	C	A	A	A	A	C	A	A	A	C
Zircon	A	C	C	C	C	C	C	A	C	C	C	F	A	A	C	S	C	A	A	C	S
Zoisite																	R				
Light fraction Chert (detrital)			+					+			+		+	+	+	+					
Feldspar[3]	‡	‡	‡											+							
Glauconite			+					+										+			
Muscovite	+	+	+		+	+		+									+	+	+	+	
Quartz	predominating mineral in the basal Chepultepec sandstone																				

EXPLANATION

A = 19+% (abundant)
C = 13–18% (common)
F = 7–12% (frequent)
S = 4– 6% (scarce)
R = 1– 3% (rare)

+ = relatively few grains
‡ = relatively common
} no count was made

[1] Numbers refer to amount of heavy minerals separated per sample.
[2] Pyrite and glauconite altered to limonite in several cases.
[3] Feldspar at location 23 is albite—probably authigenic.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 30, NO. 2, PP. 241–248
PLATE 1, FIGS. 1–3, JUNE, 1960

INDIANA PAPER COAL: COMPOSITION AND DEPOSITION[1]

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ABSTRACT

The term "paper coal," previously applied to a coal in the U.S.S.R., describes a coal found in Parke County, Indiana. In contrast to the Russian coal, which consists of cuticles of arborescent lycopods, the cuticles of the Indiana paper coal resemble *Sphenopteris bradfordii* Arnold, the foliage of a seed fern.

Exinite (cuticles and spore exines) constitutes 23.5 percent of the coal seam where it is unweathered. The papery texture occurs only where weathering has removed the vitrinite and has left a mat of resistant cuticles.

Spore analyses indicate that the seam is one of the upper Pottsville coals. Many sporangia from the paper coal are composed of small, round non-sutured spores and an outside layer of spores resembling *Torispora* Balme.

Cutinization suggests that these plants could store water. Fresh water periodically feeding into a saline swamp could have been adequate to sustain these xerophytic plants. Trace element analyses substantiate the belief that water conditions were predominantly marine.

Cutinite isolated from the coal has a calorific value of 16,700 *B.T.U.* per lb and a volatile matter content of 85 percent on a dry, ash-free basis. Because cutinite has such a high volatile matter content similar cuticular coals possibly can be utilized most efficiently as hydrocarbon sources.

INTRODUCTION

Coal is a rock composed of a heterogeneous accumulation of altered plant tissues. The chemical and physical characteristics of any coal seam or part of a seam are affected by the kinds and amounts of the contributing plant tissues. A chemically and texturally abnormal coal can result from concentrations of certain tissues which are found in minor amounts in typical coals. An example of such abnormal coal in the Pennsylvanian System of Indiana was discovered recently by the senior author. The upper part of this coal seam, exposed in the highwall of a small strip mine in Parke County, Indiana, is flexible and brown and looks somewhat like the edges of a book made of coarse brown paper. This papery texture is caused by an abundance of plant cuticle. A similar cuticular coal in the Moscow Basin, U.S.S.R., was called "Blätterkohle" by Auerbach and Trautschold (1860, p. 26) and referred to as "Papierkohle" by Zeiller (1882, p. 218). Because of the textural similarity of the Indiana and Russian deposits, the name "paper coal" is also applied to the Indiana material.

[1] Published by permission of the State Geologist, Indiana Department of Conservation, Geological Survey, Bloomington, Indiana. Manuscript received August 8, 1959.

LOCATION

This paper coal seam was discovered in a strip mine in the SW¼SW¼ sec. 27, T. 16 N., R. 7 W., Parke County, Indiana (fig. 1). The only two known outcrops of the coal, indicated by the letters "A" and "B" in figure 2, occur along branches of Sand Creek. A channel sandstone cuts out the coal between the two outcrops.

DESCRIPTION

At the south end of the highwall which constitutes exposure "A" the seam is 16 in thick, but only the upper 4 to 6 in is papery; the lower 10 to 12 in is neither papery nor cuticular[2] but is friable. The top of the seam makes a sharp contact with the channel sandstone previously mentioned. The coal is weathered and contains clay and sand which probably have been introduced by circulating ground water. Fine rootlets, presumably derived from plants which grew on the hill where the coal originally cropped out, penetrate the seam and probably contributed to the weathering. The papery texture is evident only near the face

[2] The terms "papery" and "cuticular" are not used synonymously in this report. A cuticular coal (one containing an abnormally high concentration of cuticular remains) need not display a papery texture.

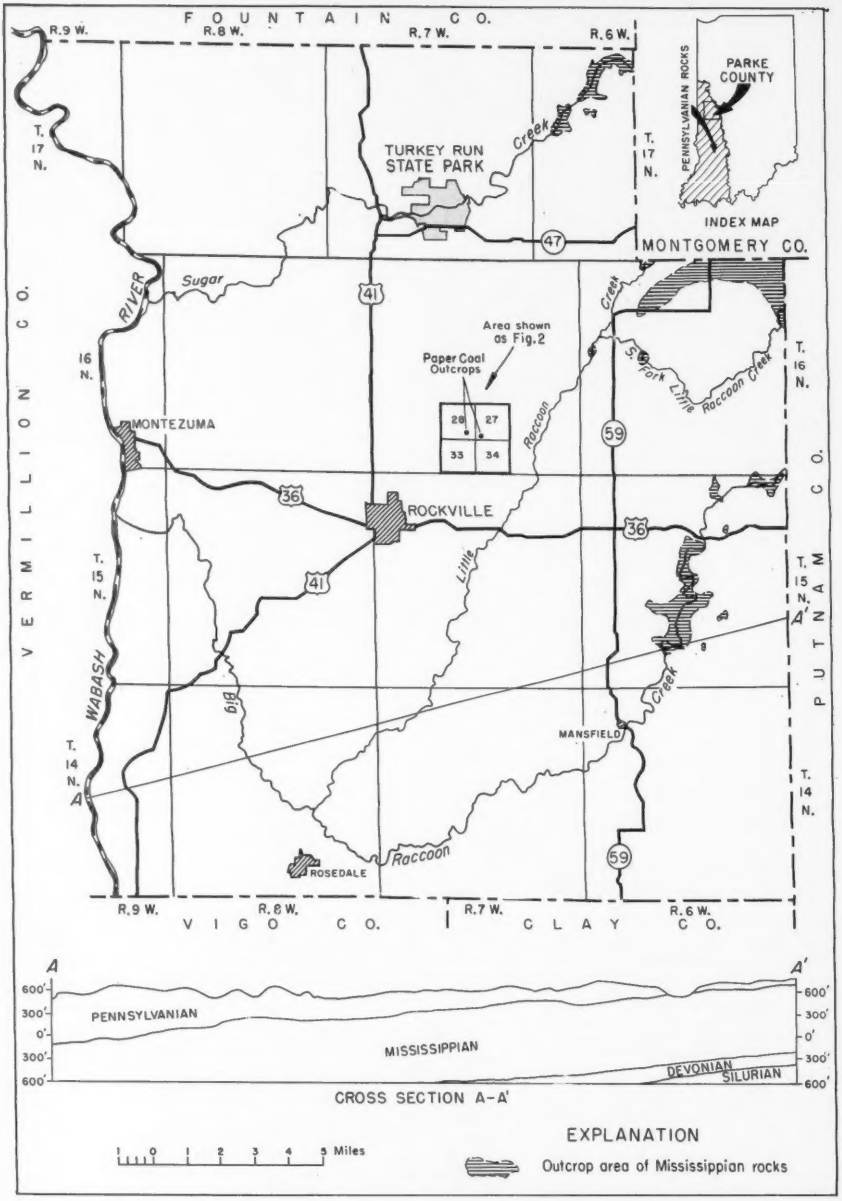

FIG. 1.—Map of Parke County, Indiana, showing location of paper coal sites. Modified from Wier and Wayne, 1953.

where weathering has removed the vitrinite and has left a residue of partially separated, flexible cuticular material.

Recent stripping has uncovered the seam for a distance of 70 ft northward. Along this cut the seam remains 16 in thick, but the sandstone contact rises and the coal grades upward into a foot of coaly shale. The upper 6 in of coal is not papery but exhibits such canneloid characteristics as dullness, lack of banding, and conchoidal fracture. Thin sections of the upper 6 ins of coal and of the overlying shale show, however, that they also contain abundant cuticles.

Only float material exists at exposure "B" in the vicinity of very old stripping activities. All of the float material is weathered and thus is papery.

A block of the paper coal is shown in plate 1, A. Because of the lamellar character of the cuticles, the coal tends to break along the bedding planes. The papery texture is most obvious along cleats (joints), which aid in the removal of blocks like the one

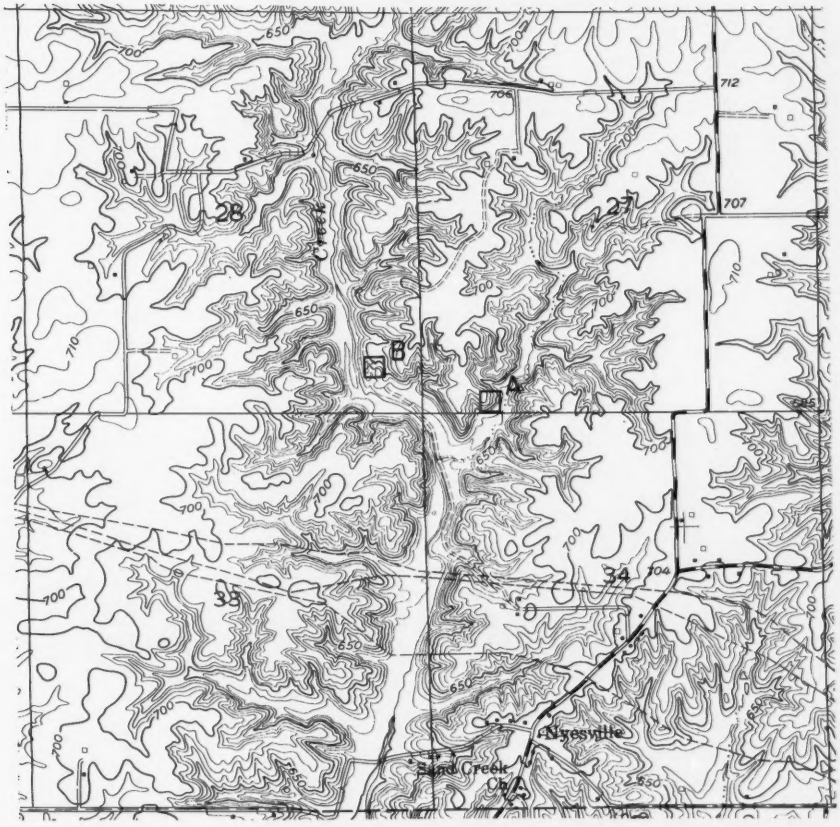

FIG. 2.—Topographic map showing detailed locations of paper coal sites. From part of U.S.G.S. Rockville Quadrangle map, 1955 edition, 7½-minute series.

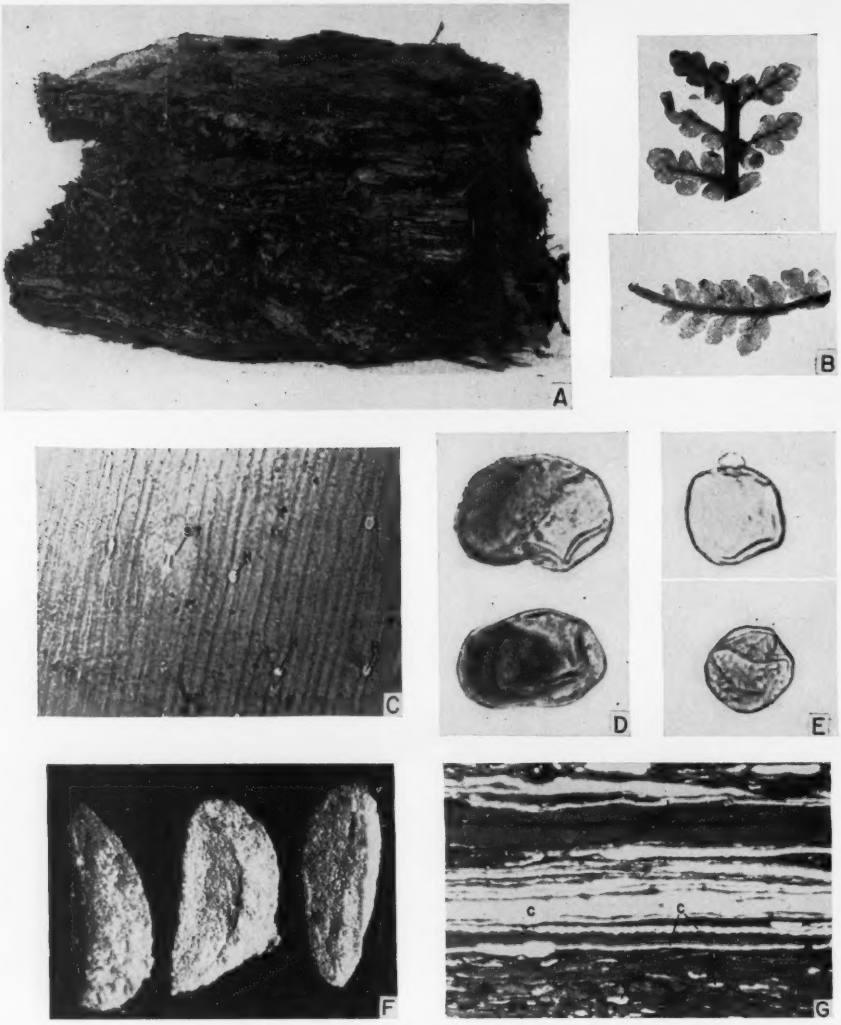

PLATE 1

A. Block of paper coal, ca. ½×.
B. Two isolated cuticles of sphenopterid pinnules, 3.2×.
C. Cuticle showing stoma (ST) and hair openings (H), 120×.
D. Two specimens of *Torispora* from sporangia in paper coal, 1270×.
E. Two specimens of unclassified spores from sporangia in paper coal, 1270×.
F. Three sporangia from paper coal. These are composed of a central mass of spores shown in E and an outside layer of *Torispora* shown in D, 32×.
G. Thin section of paper coal perpendicular to bedding. C=cuticles, SP=spores, remainder vitrinite, 120×.

pictured. The interiors of such blocks are more solid than the severely weathered part adjacent to the cleats.

PALEOBOTANY

Papery sheets were peeled from the weathered coal and treated with potassium hydroxide to remove any remaining vitrinite. Individual cuticles of twigs and leaves then were picked by hand from samples dispersed in water. Sporangia and megaspore exines also were picked from the weathered coal.

In shape and size the isolated envelope-like cuticles resemble the foliage of *Sphenopteris bradfordii* Arnold (Arnold, 1949, p. 204), a seed fern. Plate 1, B shows two representative specimens. Cuticles derived from the rachides, the stemlike structures that bore the pinnae, also have been isolated. The absence of thick anthraxylon suggests that the cuticular part of the seam is composed solely of the remains of this thin, fernlike foliage embedded in a vitrinite groundmass. In contrast to the fernlike cuticular elements of Indiana paper coal, the Russian paper coal is composed of cuticles of arborescent lycopods.

Several types of openings have been observed in the *Sphenopteris* cuticles. A stomatal opening, with impressions of its guard cells, is indicated by "St" on plate 1, C. The most abundant type of openings, indicated by the letter "H" on plate 1, C, probably is caused by emerging hairs. Both pinnule and rachis cuticles exhibit the same types of openings.

DEPOSITIONAL ENVIRONMENT

The thick cutinization and the hairy aspect of the cuticles suggest that the spenopterids were xerophytic or drought-resistant. Cuticle deters desiccation, and plants which are heavily cutinized can conserve their water during periods when water is unavailable. The preservation of these plant tissues as coal, however, indicates growth and deposition in a swamp or similar aquatic environment.

The probable solution to the apparent paradox of "drought-resistant" plants in an aquatic environment is that water was not lacking but was toxic and unsuitable for plant use. Salinity is an obvious cause of such toxicity. The heavily cutinized xerophytes probably could have been sustained by an occasional influx of fresh water.

The lower, noncuticular part of the paper coal seam is a normal coal and is apparently composed of the remains of normal coal-forming plants which were relatively intolerant of marine conditions. The overlying shale contains imprints of *Sigillaria* and *Calamites;* this fact indicates a return to fresh-water conditions after the deposition of the paper coal. The deposition of the paper coal probably occurred during a period of marine transgression.

Chemical data support the assumption of marine influence in the paper coal layer. According to Degens, Williams, and Keith (1957), marine depositional loci are indicated by concentrations of boron and nickel in Pennsylvanian shales. Gallium and chromium are indicative of fresh-water deposits. Table 1 lists the abundances of these four elements in the paper coal and in adjacent strata. Boron and nickel are more abundant in the coal than they are in the shale above the coal. Gallium and chromium are more abundant in the shale and the noncuticular part of the seam than they are in the cuticular part of the seam. The shale, therefore, appears to be a fresh-water deposit, particularly on the basis of the relative abundance of gallium and relative scarcity of boron and nickel. The cuticular part of the coal contains little gallium and chromium but considerable boron and nicke.

TABLE 1.—*Concentrations (in P.P.M.) of gallium, chromium, boron, and nickel in ash of paper coal, adjacent strata, and earth's crust*

Sample Designation	Gallium	Chromium	Boron	Nickel
Paper coal (cuticular)	—	0.005	0.1	0.005
Paper coal (non-cuticular)	0.01	0.01	0.1	0.01
Shale above coal	0.05	0.01	0.002	0.0005
Earth's Crust (Mason, 1952)	0.0015	0.02	0.0003	0.008

and thus appears to be a marine deposit. The noncuticular part of the coal seam probably was deposited in a fresh-water swamp where occasional marine encroachments resulted in accumulations of boron and nickel.

PALYNOLOGICAL COMPOSITION AND STRATIGRAPHIC POSITION

Torispora, an acorn-shaped spore (pl. 1, D) first reported by Balme (1952, p. 183), is abundant in the maceration residues of Indiana paper coal. *Torispora*, which constitutes 23 percent of the paper coal spore assemblage, and a small (20μ) round spore that lacks a distinct suture line (pl. 1, E) are the dominant spores. The small spore constitutes 20.5 percent of the spore population.

Horst (1957, p. 698) interpreted *Torispora* bodies as isolated wall cells of sporangia to which he gave the name *Bicoloria*. Sporangia are found abundantly in the paper coal and about two dozen of these were isolated from the coal and then disaggregated (pl. 1, F). The outer layer of these sporangia consists of *Torispora*, and the central mass of the sporangia is composed of the unassigned, small, thin-walled spores. These small, central spores are probably the functional spores. The exposed part of the *Torispora* exine is thick and apparently served the function of a sporangial wall. The fact that these two spores constitute more than 40 percent of the total spore count indicates that there is a relationship of these spores to the *Sphenopteris* foliage that makes up the bulk of the paper coal.

The upper bench of a coal lying 15 ft below the paper coal has a spore assemblage similar to that of the Lower Block c zone (upper Pottsville, see Guennel, 1958, p. 25) as is shown by the high *Lycospora* count. The "*Torispora*" count shown in the graph of spore genera (fig. 3) includes the unclassified spores that are apparently derived from the same sporangia as *Torispora*. By ignoring the high *Torispora* percentage, which must be interpreted as a singular ecological phenomenon, one can recognize a relationship between the paper coal graph and the Upper Block b zone graph.

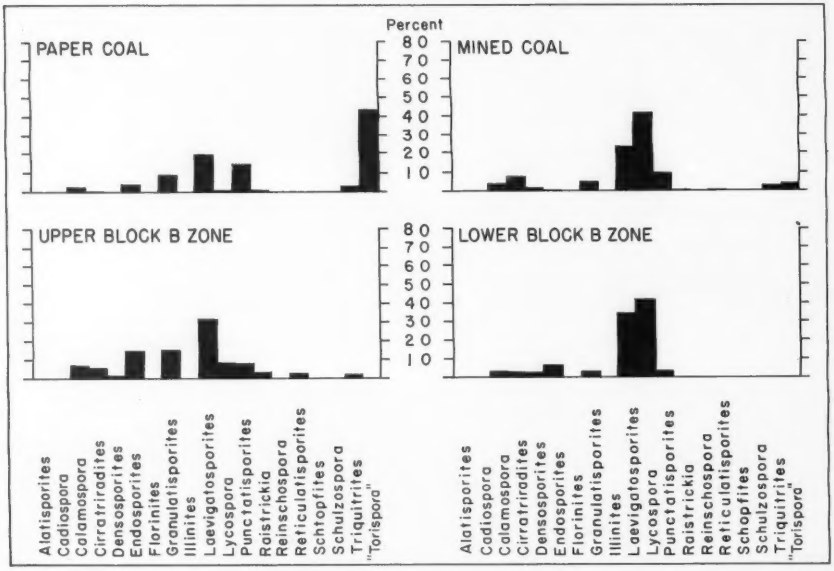

FIG. 3.—Histogram showing relative abundances of spore genera in paper coal, in coal mined 12 to 15 ft below paper coal, and in two Block coals.

TABLE 2.—*Petrographic composition (in percent) of unweathered cuticular coal*

Vitrinite, Anthraxylon	24.1
Attritus	51.8
Exinite, Cutinite	15.8
Sporinite	7.7
Micrinite	Trace
Fusinite	0.2
Mineral matter	0.4

PETOGRAPHIC COMPOSITION

Plate 1, G is a photomicrograph of a thin section of relatively unweathered paper coal. Cuticles (indicated by "C") and spore exines (indicated by "SP") are embedded in a matrix of light-red vitrinite. The vitrinite matrix is very sparse in highly weathered paper coal.

Quantitative petrographic data that were procured from thin sections of relatively unweathered paper coal are presented in table 2. Although the weathered paper coal appears to consist almost entirely of cuticular remains, the less weathered coal from which the thin sections were prepared contains only 15.8 percent cutinite. Exinite (cutinite and spore exines combined) constitutes 23.5 percent of the coal. Both the cutinite and total exinite contents are, of course, far above average for Indiana coals, whereas 24.1 percent anthraxylon is well below average.

CHEMICAL COMPOSITION

Table 3 lists proximate analysis data. The volatile matter content of the paper coal and of the overlaying shale (66.5 and 88.4 percent respectively of the dry, ash-free samples) is well above average for Indiana coals. More than 400 coal samples analyzed by the Indiana Geological Survey during the last 4 years contained an average of 47.9 percent volatile matter on a dry, ash-free basis. Pure cutinite isolated from the paper coal was found to contain 85 percent volatile matter. The coal mined in the pit (15 ft below the paper coal) is of high volatile C Bituminous rank (12,350 *B.T.U.* per lb. of moist, mineral-matter free sample). The paper coal, however, is *apparently* of subbituminous rank (10,213 *B.T.U.* per lb of moist, mineral matter-free sample). The low calorific value, however, is apparently not a function of a low degree of metamorphism but rather is a function of weathering. Pure cutinite from the paper coal contains more than 16,700 *B.T.U.* per lb of dry, ash-free sample.

All Indiana and Illinois coal seams are generally considered to be high in sulphur. Analyses of more than 400 channel samples of Indiana coal seams indicate that most contain more than 2 percent sulphur. The paper coal samples contained only 0.62 percent sulphur.

CONCLUSION

Because of its high volatile content, paper coal may be a potential hydrocarbon source. Unfortunately, however, this seam is of limited areal extent. Three samples of coals containing abnormally high amounts of cutinite have been found in Indiana since the discovery of the seam described in this report. One of these is slightly weathered and thus is papery. Another is canneloid, and the third appears megascopically to be a normal, banded coal. The papery texture of weathered cuticular coals and the canneloid appearance of some of the fresh cuticular coals can serve as a means of identifying similar deposits. It is hoped that this report will stimulate interest in the variability of coal types so that each type will be used eventually in the most effective manner.

TABLE 3.—*Proximate analyses of paper coal, adjacent sediments, and cutinite*

Sample Designation	Moist. % (AR)	Ash % (AR)	Vol. M. % (DAF)	B.T.U. lb. (AR)	B.T.U. lb. (MMF)	Sul. %
Paper coal, channel	14.3	14.9	66.5	8,896	10,213	0.62
Lower part paper coal seam (non-cuticular)	16.1	14.0	59.8			0.70
Cuticular shale above	2.5	68.9	88.4			0.34
Coal 15 ft below	14.7	7.7	42.8	11,411	12,347	4.1
Cutinite, pure, picked	11.0	10.0	84.7	13,320	15,515	0.21

(DAF = dry, ash-free; AR = as-received; MMF = moist, mineral-free, Parr.)

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 30, NO. 2, PP. 249–274
FIGS. 1–13, JUNE, 1960

SEDIMENTS OF NARRAGANSETT BAY SYSTEM AND RHODE ISLAND SOUND, RHODE ISLAND[1]

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ABSTRACT

Gravel, sand, silt, and clay content was determined for 942 samples from the bays and adjacent inner shelf to a distance of some 20 miles off the Rhode Island coast.

In the Narragansett Bay system clayey silt and sand-silt-clay are the most abundant sediments although sand is important locally. Neither the Bay system nor the inner shelf contain a predominant clay type of sediment. Primarily, sediments are derived from the unconsolidated subaerial and subaqueous glacial and post-glacial deposits. It is believed that the sediment available for deposition is composed of some fine and very fine sand, silt, and clay, but the quantity is very small. During the period in which present environmental conditions have been effective clayey silt and sand-silt-clay have accumulated for the most part in the more protected middle and upper areas of the Bay system. The depositional sites for the finest of these sediments may be the result of the peculiarities of surface tidal current flow. Areas which show marked gradational changes in texture probably indicate significant local variations in current activity along the bottom interface. In general, toward the lower reaches of the Bay passages the sediments show a progressive change to coarser textures.

On the inner shelf the predominant sediment type is clean, well-sorted sand. Apparently gravel is concentrated along two major trends which are generally associated with the two submarine elevation features that cross the area. A well-defined depositional zone of sandy silt and silty sand, believed to be the result of non-tidal drift, begins near the entrances to Narragansett Bay and follows the trend of a winding submarine slope toward the southwest and Block Island Sound. A tongue of sand which lies adjacent to the Rhode Island mainland from Point Judith into lower West Passage owes its origin to the northerly moving longshore current which pushes into the Bay from Block Island Sound.

In the Bay system and certain areas on the inner shelf unburied glacial or post-glacial lag deposits juxtapose with recently accumulated fine sediments.

Present environmental forces are not responsible for the creation of the major submarine topographic features of the region, but in the Bay depositional processes of recent environmental conditions have had considerable success in burying sedimentary deposits of previous environments.

INTRODUCTION

Narragansett Bay and Rhode Island Sound lie along the southern coast of New England between Long Island, New York and Cape Cod, Massachusetts (fig. 1). In this region, the coastline is relatively low but is most irregular and is characterized by numerous branching bays, salt water ponds, peninsulas, rugged headlands, islands, sea stacks, rocky shores, sandy beaches, bay bars, spits, tombolos, salt water marshes and an irregular sea bottom. According to Shepard's classification of coasts and shorelines (1948, p. 73), this general coastal region may be designated basically as a glaciated coast type which has been modified by marine agencies.

The Narragansett Bay system, an extensive series of deep but connected embayments known locally as Narragansett Bay proper, Greenwich Bay, Mount Hope Bay, and the Sakonnet River, is located almost exclusively in Rhode Island with the exception of a small segment of Mount Hope Bay which extends into southern Massachusetts (fig. 2). In contrast to the east-west orientation of Long Island Sound, Buzzards Bay, and Vineyard Sound, the Narragansett Bay system shows a distinct north-south trend. From Brenton Point to Nayatt Point, along the main axis of the Bay system, the distance is approximately 16 miles with a maximum width of almost 11 miles. Three large islands, Conanicut, Prudence, and Aquidneck Islands, and numerous small islands lie within the confines of this Bay system. Aquidneck Island separates the Sakonnet River or Passage from the main part of the Bay whereas Conanicut and Prudence Is-

[1] Manuscript received July 15, 1959. Contribution no. 27 from the Narragansett Marine Laboratory.

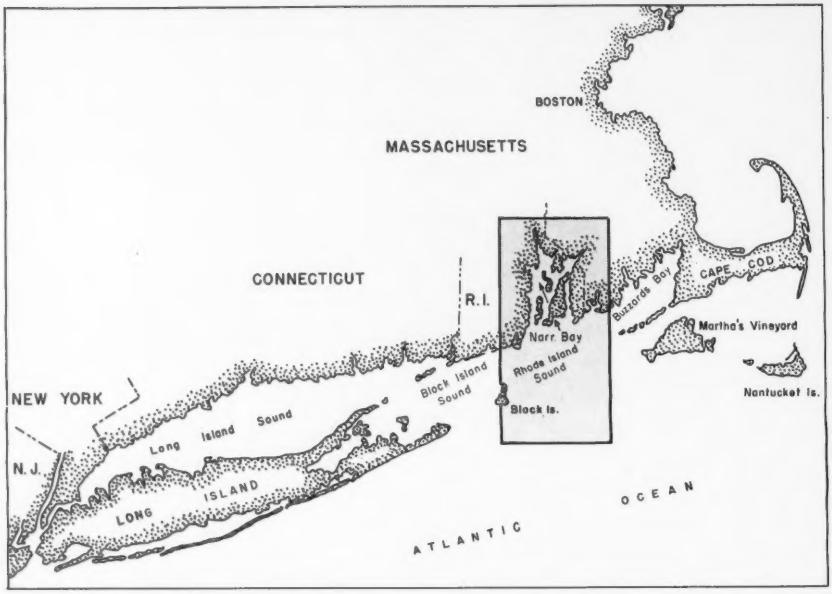

FIG. 1.—Index chart showing location of Narragansett Bay, Rhode Island, and Rhode Island Sound.

lands divide Narragansett Bay proper into two long and narrow passages known as East and West Passages.

Although there are a number of streams in the region which discharge into the Bay system, the most important ones are the Providence, Blackstone-Seekonk, and Taunton Rivers. The combined flow of the Blackstone-Seekonk and Providence Rivers enters the upper Bay on the north just below the city of Providence at Nayatt Point, whereas the Taunton River empties into Mount Hope Bay at Fall River, Massachusetts on the northeastern side of the Bay system.

Rhode Island Sound lies adjacent to the Narragansett Bay system and separates the Bay from the open Atlantic Ocean. It is bounded on the west by Block Island Sound, on the east by Buzzards Bay and Vineyard Sound, and on the south by a line connecting Martha's Vineyard and Block Island (fig. 1).

The area sampled includes the lower reach of the Providence River, the Narragansett Bay system, and that part of Rhode Island Sound and its approaches defined by the following coordinates: Longitudes 71°W and 71°35'W; Latitude 41°N (fig. 1). This area is approximately 47 miles in length, of which 28 miles are seaward of the Bay entrance, and varies in width from one mile at the lower end of the Providence River to approximately 25 miles in the open sea.

The purpose of this paper is to bring to the attention of workers in sediments the variations that exist in the distribution of sediment types and certain textural components within adjacent bay and inner shelf environments for a region which is still basically controlled by former glacial action.

FIELD AND LABORATORY PROCEDURES

A total of 942 sampling stations was occupied in the study area shown in figure 1. Samples from the Bay were obtained by means of a grab sampler, the Petterson Dredge, whereas those on the shelf were collected by a dwarf orange peel bucket (Hough, 1939, p. 660). In the Bay a basic grid system was chosen which positioned

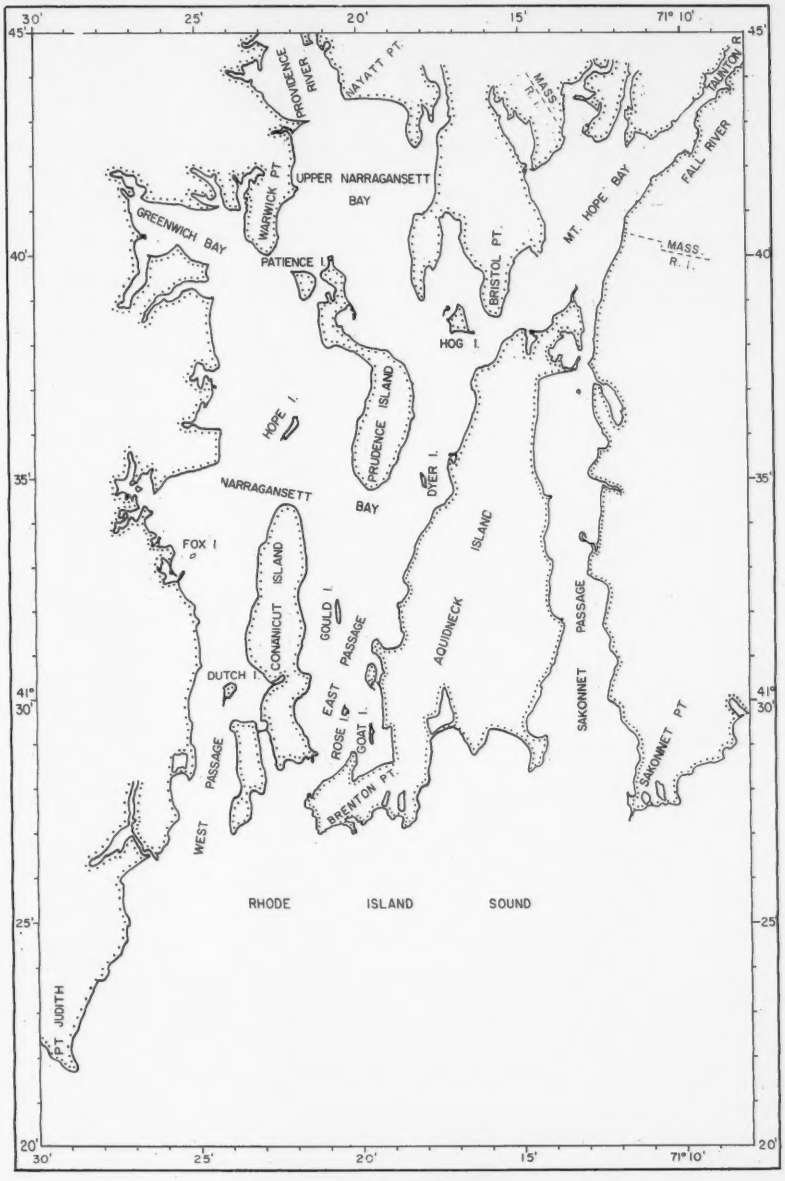

FIG. 2.—General location chart for Narragansett Bay.

sampling stations at intervals of one-half minute in latitude and longitude, although additional stations were occupied in Greenwich Bay, the upper end of the Sakonnet Passage, and the entrance to Mount Hope Bay at Bristol Point (fig. 2). The offshore sampling stations were spaced at intervals of one minute in latitude and longitude except for the outermost reaches where the interval was irregularly opened to two minutes or more.

In the laboratory, only the primary textural properties (that is, the proportions of gravel, sand, silt, and clay) of the bottom samples were investigated. First the field samples were dried, disaggregated, and then passed through a 2 mm screen. After weighing, the undersize sediment was split down to a 50 gm fraction which was further disaggregated and finally dispersed. The Bouyoucos method (1936) of hydrometer analysis was used to determine the proportions of silt and clay in the samples. After sedimentation was initiated, a hydrometer reading was made at the end of 60 minutes. This reading corresponded to the clay size particles (defined by Bouyoucos, 1936, p. 228) as particles smaller than 5μ) still in suspension. After the clay was decanted, the sand-silt admixture was dried and sieved on a 62μ screen. The amount of sediment retained on this screen was recorded as sand.

Because the Narragansett Bay region contains a wide range of sediment sizes (boulders, cobbles, pebbles, granules, sand, silt, and clay), it has been found desirable to reduce the number of these components to four basic groups based on particle size. These are gravel, sand, silt, and clay. The term gravel is used for particles larger than 2 mm; sand is used for those particles whose diameters are between 2 and 0.062 mm; silt denotes grains between 62 and 5μ; and clay is used for particles smaller than 5μ.

A lithologic tetrahedron, as suggested by Krumbein and Sloss (1951, p. 121), was applied to show the textural relations among the sediments. This tetrahedron with vertices gravel, sand, silt, and clay provided a basis for dividing the four triangular faces into a number of textural classes. The arrangement of class lines and the subsequent class names followed the recommendations of Shepard (1954, p. 157) but were modified to include the gravel component.

TOPOGRAPHY

Narragansett Bay System

The underwater topography of the Narragansett Bay System is quite irregular because of the presence of shoals, ledges, submerged valleys, and holes on the Bay floor (fig. 3). This description is based on soundings from local U. S. Coast and Geodetic Survey Charts.

In Mount Hope Bay the bottom surface is essentially flat and featureless over most of the area with depths averaging 18 ft. Two dredged channels deeper than 28 ft are maintained adjacent to the eastern shore, and these join the Taunton River channel at Fall River, Massachusetts. At the entrances to this embayment near Bristol Point and Tiverton, narrow valleys are cut in the Bay floor. Between Bristol Point and Aquidneck the valley reaches a depth of 83 ft whereas at Tiverton the greatest depth in that valley is 61 ft. Aside from these entrance valleys the deepest natural occurring spot in Mount Hope Bay is found near Fall River adjacent to the eastern shore where a depth of 41 ft. is reported.

In the Sakonnet Passage the submerged valley leading from Mount Hope Bay at Tiverton is traceable as far south as the mouth of the Passage and dominates the topography in the area. This valley does not show a constant gradient throughout its length but is marked by several spots of deeper depths. Although the average depth of this Passage is 24.5 ft, these deeper spots in the valley are 45 and 65 ft. At the entrance to Rhode Island Sound the soundings measure about 60 ft.

One of the most distinctive topographic features in Narragansett Bay itself is the drowned valley which extends along the eastern side of the Bay from the Providence River to Rhode Island Sound, a distance of 18 miles. The valley floor does not show a uniform gradient throughout its length but is undulating in longitudinal profile, especially in lower East Passage. In the vicinity of Hog Island a tributary valley, maximum depth 88 ft, leads into Mount Hope Bay.

The greatest depths in the entire Bay sys-

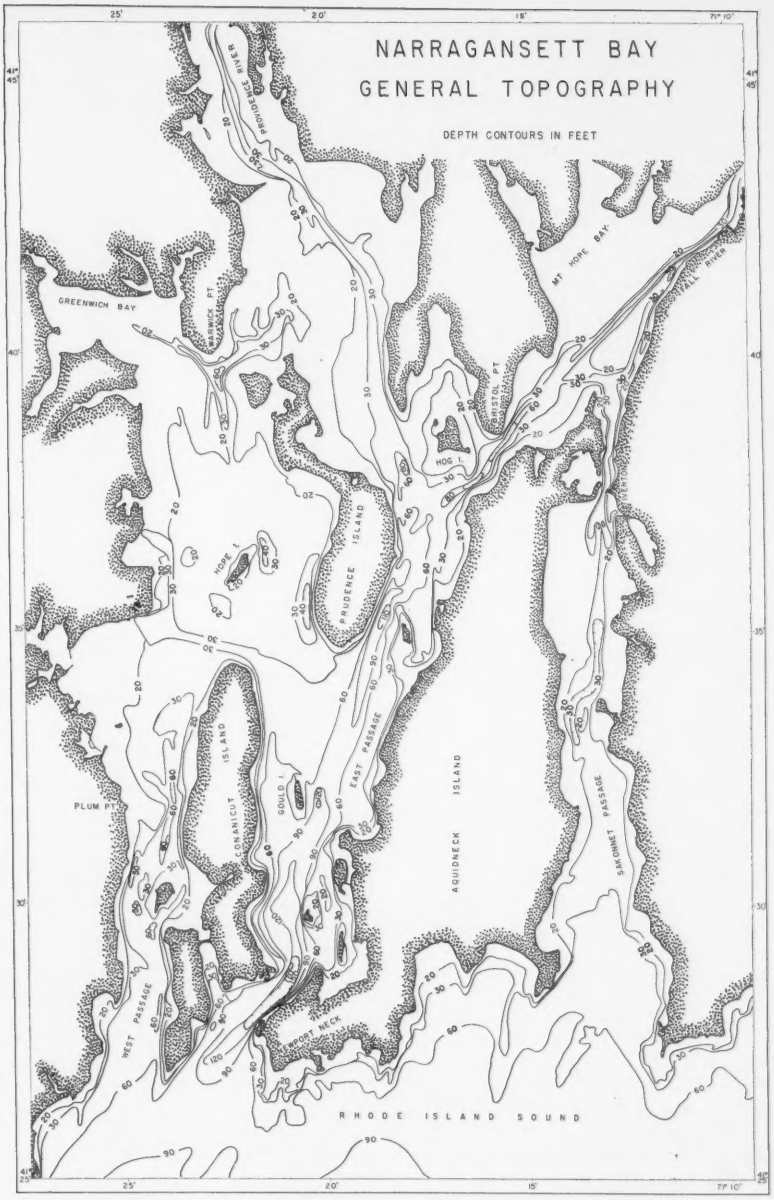

FIG. 3.—BOTTOM topography of the Narragansett Bay system.

tem are found in East Passage. Soundings of greater than 100 ft occur adjacent to Prudence Island then decrease somewhat toward Gould Island but again increase to more than 150 ft toward the mouth of the Passage. In the constriction between Conanicut Island and Newport Neck a depth of 188 ft has been recorded (S. D. Hicks, personal communication). At the mouth of the Passage soundings are between 80 and 90 ft.

The western part of Narragansett Bay, as a whole, is much more shallow than the eastern side. In the vicinity of Warwick Point a short submerged valley with a tributary leading to Greenwich Bay connects upper Narragansett Bay with West Passage. Maximum depth in this short valley is 74 ft. From the upper end of West Passage this valley gives way to an extensive, submerged, shallow plain. North of Conanicut Island an east-west dredged channel of 32 ft crosses the plain to East Passage. Along the western shore of Conanicut Island several submerged valleys with local deep spots are entrenched in the Bay floor, but these cuts do not form a continuous feature to the mouth of West Passage. A maximum depth of 95 ft is located near Plum Point although the average depth of lower West Passage is only 24.5 ft. At the mouth of West Passage soundings of 60–70 ft are recorded.

Rhode Island Sound

The main features of the bottom topography in Rhode Island Sound are expressed by a pattern of low elevations and drowned valleys that occur on the sea floor (fig. 4). The bathymetric contours were drawn from soundings recorded on U. S. Coast and Geodetic Survey Hydrographic Survey Charts Nos. 6443, 6444 and 6445 dated May to September 1939.

The present bottom relief is dependent to a large extent upon two elevated areas which cross the Sound. The inner one, a discontinuous belt of high spots, extends from Point Judith Neck on the west as a curving arc toward the Elizabeth Island chain on the east. From Point Judith this feature begins as a local protuberance, trending toward the southeast for a distance of 5 miles. From this point there is a wide gap of some 10 miles which extends toward the east. In the vicinity of Latitude 41°18′N and Longitude 71°10′W a belt of hummocky relief is traceable toward the northeast, a distance of approximately 10 miles. At this point a submerged valley, originating in Buzzards Bay, cuts through this elevated area in a north-south direction on the eastern edge of the Sound.

The outer elevated area roughly parallel to the inner belt extends from Block Island on the west across the Sound toward the east. This belt of higher elevations is a continuous feature except for a 5 mile gap near Block Island.

Between the mainland and the inner elevated belt the bottom has a general regional slope toward the south and southwest on the northeastern side but the slope changes to a south and southeast direction in the vicinity of Point Judith. These slopes converge in a semi-basin feature immediately south of Narragansett Bay itself. A broad valley leads from this basin toward the south through the gap in the inner elevated area. It is noteworthy that none of the valleys which characterize the lower reaches of West, East, and Sakonnet Passages of the Narragansett Bay system extends seaward their respective mouths and also that the depths adjacent to the mouth of the Eas Passage are much less than those recorded in the submerged valley of lower East Passage.

Several well-defined but apparently independent valley systems are associated with the area between the two elevated belts. On the east the valley which leads from Buzzards Bay joins a broad valley traceable to Vineyard Sound to form a trunk valley trending toward the southwest between the two elevated areas. This latter valley, with a maximum depth of 215 ft, transects the outer elevated area just east of Block Island. At this point a tributary valley leading north a short distance meets this trunk valley.

Five miles southwest of Point Judith soundings indicate the presence of a poorly-defined valley feature. As the trend of this valley is followed toward the west its outline becomes well-marked and is traceable for several miles in a westerly direction beyond the limits of the Chart (fig. 4). The greatest depth in this valley within the confines of Rhode Island Sound is 176 ft. Apparently,

the broad valley leading from the basin adjacent to Narragansett Bay joins this westward trending valley.

GEOLOGY

General Geology of Rhode Island and Southern Massachusetts

One of the most distinctive features of the geology of Rhode Island and southeastern Massachusetts is the Narragansett Basin (Shaler and others, 1899; Emerson, 1917; Quinn, 1953) shown in figure 5. This ancient structural basin occupies most of eastern Rhode Island and extends northeastward into Massachusetts. Along its axis of greatest length, the basin measures a distance of more than 50 miles and has a maximum width of approximately 30 miles. The rocks

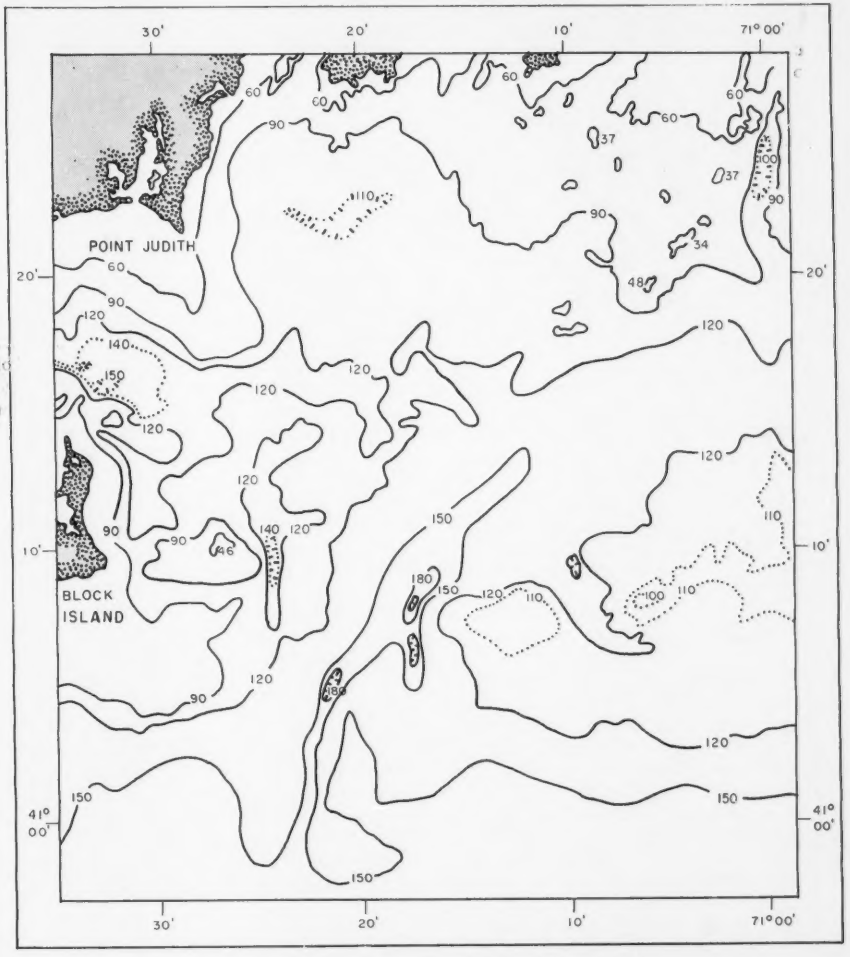

FIG. 4.—Bottom topography of Rhode Island Sound.

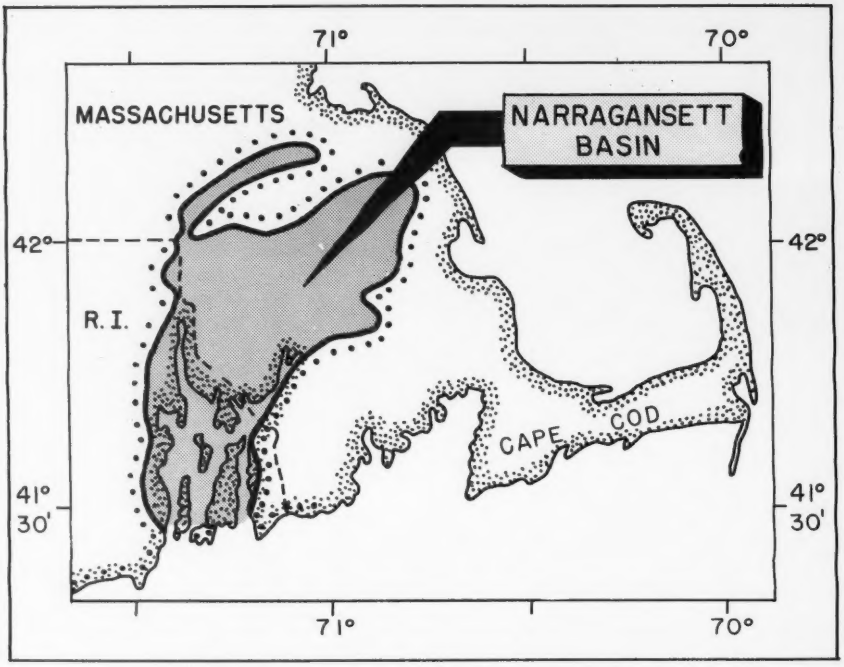

FIG. 5.—Location of the Narragansett Basin (adapted from Shaler and others, 1899, p. 110).

in this basin are mostly sedimentary conglomerates, sandstones, shales, and metaanthracite coal beds of Pennsylvanian age which show increasing effects of metamorphism toward the south (Quinn, 1953, p. 267–68). This basin is a topographic depression as well as a structural basin because these sedimentary rocks in the Narragansett Basin are relatively weak in resistance to erosion and weathering (Quinn, 1953, p. 264). The present Narragansett Bay system occupies the lower seaward end of this depression.

In general the rocks of the Narragansett Basin are surrounded by pre-Pennsylvanian igneous and metamorphic rocks with the exception of several small depressions of Pennsylvanian sediments that are located near the northwestern boundary of the Narragansett Basin (Quinn, 1953, p. 265) and several late or post-Pennsylvanian intrusive granites found along the lower southwestern border of the basin (Quinn and others, 1957, p. 558).

For the most part, the bedrock surface is concealed by a coating of Pleistocene glacial drift (Shaler and others, 1899, p. 102). These stratified and unstratified deposits occur in several different forms (for example, ground moraine, ice-contact deposits, outwash plains, and others) and provide a thick blanket over most of the lowland and a thin cover over most of the upland (Allen, 1956; Bierschenk, 1956). In general this drift is composed of well-sorted sands and gravels as well as unsorted variable mixtures of gravel, sand, silt, and clay (Allen, 1956; Bierschenk, 1954, 1956; Smith, 1955, 1956). Apparently sand and silt are the most common constituents in the tills (Moultrop, 1956, p. 10).

However, there are some recent sediments such as river terrace deposits, alluvium, swamp deposits, and sand dunes which

occur as surface materials on the land in local areas as well as a greater quantity of recent marine sediments that are found on the Bay floor itself. These later sediments, derived essentially from glacial deposits, are expressed in part by a variety of forms such as bay beaches, spits, cuspate bars, and tombolos.

General Geology of Rhode Island Sound

Some information on the subsurface geology of Rhode Island Sound and its approaches is provided from several geophysical surveys in the coastal region (Ewing and others, 1950; Oliver and Drake, 1951; and Miller, 1952). Apparently, the crystalline rock surface gently dips toward the southeast beneath Rhode Island Sound and its approaches, and the overlying sediments, mostly unconsolidated deposits, thicken from 200 ft 3 miles south of Point Judith, Rhode Island (figs. 1 and 2) to 2000 ft 20 miles southeast of Block Island (Oliver and Drake, 1951, pl. 2). These sediments probably range in age from early Upper Cretaceous to Recent judging from exposures on Martha's Vineyard (Ewing and others, 1950, p. 887).

From a magnetometer investigation in coastal Rhode Island waters, Miller (1952) concluded that the structural Narragansett Basin extends south under water at least 10 miles beyond its apparent subaerial termination.

Pre-glacial History

Quinn and others (1948, p. 35) believe that the development of the present day topography in the Narragansett Bay region had its beginning in the early part of the Tertiary Period when most of New England is thought to have been eroded by streams to a general low level. According to Quinn and others (1948, p. 35), at about the middle of the Tertiary this surface of low relief was uplifted and dissected by streams two or more times before the Pleistocene glaciation. Apparently the Narragansett Bay region stood higher above sea level than at present as evidenced by the buried river valleys of the region (Roberts and Brashears, 1945; Quinn and others, 1948; Bierschenk, 1954, 1956; Allen, 1956). Recent work suggests that these deep valleys continue beneath the present Bay sediments reaching depths of more than 320 ft near the entrances to the Bay (U. S. Army Corps of Engineers, 1957, pl. E5 and E6). A recent boring made in the Sakonnet Passage near Tiverton (W. B. Allen, U. S. Geological Survey, personal communication, 1958) reports the bedrock floor at a depth of 378 ft (fig. 2). However, borings made on various parts of the coast of northern New England and along major valleys in Connecticut show that the bedrock floors of the river valleys lie at depths within the range recorded for the Narragansett Bay region (Flint, 1947, p. 448).

Although most of the details concerning the courses of the buried valleys beneath the Bay and Sound are lacking, it seems evident that there were three major trunk channels draining the present Narragansett Bay lowland (fig. 2). On the west an old river system entered the present Greenwich Bay area from the northwest and then proceeded toward the south through West Passage. A middle river system flowed south through upper Narragansett Bay and East Passage to the sea. The old trunk channel farthest to the east entered Mount Hope Bay and then turned south by way of what is now the Sakonnet Passage. Preliminary evidence seems to show that the present Bay system channels have been displaced to the eastward of the older buried pre-glacial valleys.

Glacial History

In Pleistocene time, glacial ice began to move down from the north through these deep valleys and tributaries. It is believed that the Bay region was invaded several times by continental ice sheets during the Pleistocene epoch (Shaler and others, 1899; Quinn and others, 1948). Flint (1953, pl. 1) suggests that Wisconsin drift as characterized by an outer belt of two glacial advances, namely the older Ronkonkoma-Nantucket Moraines and younger Harbor Hill-Buzzards Bay Moraines, marks the last known invasion of glacial ice into the Narragansett Bay region (fig. 6). It is noteworthy that the greatest of these advances, the Ronkonkoma-Nantucket Moraines, reached a position which now coincides with the southern limit of Rhode Island Sound whereas the younger Harbor Hill Moraine

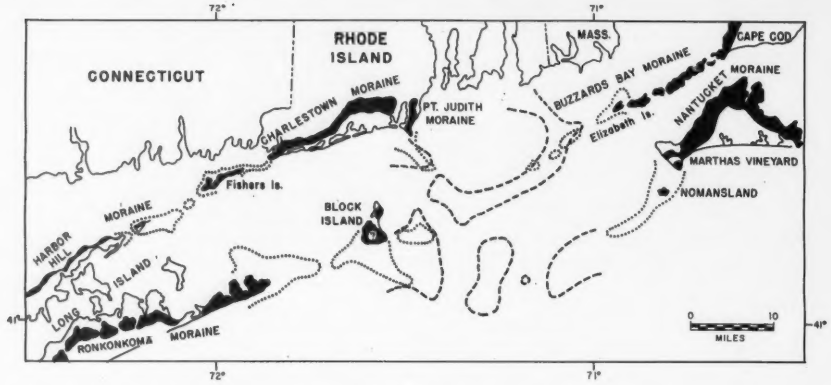

FIG. 6.—Sketch map showing outer Wisconsin drift border in coastal southern New England (adapted from J. P. Schafer, personal communication, 1958). Terminal moraines are in black; dashed lines surround areas of patches of gravelly bottom materials; dotted lines indicate location of submarine ridges.

(known locally as the Charlestown and Point Judith Moraines) extends across the southern coast of Rhode Island. In reference to these later moraines J. P. Schafer (personal communication, 1958) states:

"The Charlestown Moraine has generally been considered correlative with the moraines on Cape Cod. New support for this correlation is derived from unpublished studies of bottom sediments by the Narragansett Marine Laboratory of the University of Rhode Island. Southeast of Point Judith, a broad arcuate belt of relatively coarse sediments forms a rim in front of Narragansett Bay. This belt is inferred to be the submerged connection, partly covered by recent fine-grained marine sediments, between the Point Judith Moraine and the Buzzards Bay Moraine. According to this correlation, the Point Judith Moraine was deposited at the west edge of an ice lobe that extended from the west side of Narragansett Bay to the east side of Buzzards Bay.

"It is certain that the Point Judith and correlative Moraines . . . are of Wisconsin age. However, a reliable correlation has not yet been made with a Wisconsin subdivision."

By their erosional and depositional action, the ice sheets left a greatly modified pre-glacial topography. The old pre-glacial valleys of the Bay region were partly filled with sediments of probable glacial ice, glacio-fluvial, glacio-lacustrine, and even eolian origin.

Recent boring records suggest that an extensive and thick deposit of laminated clay and silt was laid down during or after the disappearance of the ice in the upper, middle and lower Bay areas (U. S. Army Corps of Engineers, 1957, pls. E-2, 3, and 4; American Drilling Company, Inc., personal communication, 1958).

Post-Glacial History

Although glacial ice retreated from the Narragansett Bay region in early Wisconsin time, it apparently returned several times to other sections of New England during late Wisconsin (Flint, 1953, 1957, p. 356). Undoubtedly these later advances and retreats indirectly affected the Narragansett Bay region if in no other way than causing fluctuations in sea level. However, it is uncertain as to whether times of lower sea level can be correlated with any erosion evidence.

One of the most interesting phenomena of the present Bay system is the narrow depressions which are found on the Bay floor. These depressions are best expressed in East Passage (fig. 3) although isolated segments are located at the head and lower end of West Passage and in the entrance to

Mount Hope Bay (fig. 3). Woodworth (1896, p. 168) mentions the possibility that ice remnants in the troughs of the Bay were the last to melt because of the thickness of the ice.

Shaler and others (1899, p. 73–74) suggest, after some deliberation and discussion, that these depressions are due to the direct cutting action of the ice and to the concomitant action of subglacial streams.

Bierschenk (1954, p. 19), Smith (1955) and Allen (1956, p. 8) believe that the latest ice sheet became stagnant, melted more or less in place, and then wasted down into separate blocks which occupied the larger depressions. Although their suggested explanations were not directed specifically to the Bay depressions, they should apply equally to all such features in the general area.

In nearby Buzzards Bay, Hough (1940, p. 20) attributes the deep channel near the Bay mouth and the extension of the 40-ft contour toward the head of the Bay to possible late glacial subaerial stream erosion.

Certainly these provocative hypotheses merit further consideration, but a detailed appraisal of the available data concerning these phenomena is beyond the scope of the present paper.

Depth and Nature of Unconsolidated Sediments in Narragansett Bay

Some data concerning the thickness of the sediment cover in Narragansett Bay have become available from recent borings and seismic investigations. A summary of these data are presented in table 1.

This sediment overburden undoubtedly includes materials of several modes of deposition. There are certainly deposits which owe their origin to glacial ice, glacial meltwaters as streams and lakes, stream action, possible wind action, estuarine conditions, and even marine conditions. However, until these sediments are adequately defined as to extent and origin the details of preglacial, glacial and post-glacial history will have to remain as conjecture. It has been estimated that there may be up to 15 ft of recent sediments in the Bay (U. S. Army Corps of Engineers, 1957, p. 8).

TABLE 1.—*Unconsolidated sediment thickness in Narragansett Bay*

Location	Sediment thickness (feet)
Mouth of Providence River, Upper Narragansett Bay[1]	+125
Near Patience Island, West Passage[1]	+102
Prudence Island, East Passage[1]	+100
Between Bristol Point and Aquidneck Island[2]	50 or less
Near Tiverton, Sakonnet Passage[3]	336
Near mouth of East Passage[1]	+170
Lower end of West Passage[1]	+260
Near Gould Island, East Passage[4]	+148

[1] U. S. Army, Corps of Engineers, 1957, pls. E2–6.

[2] Bierschenk, 1954, fig. 2.

[3] W. B. Allen, U. S. Geological Survey; personal communication, 1958.

[4] American Drilling Company, Inc.; personal communication, 1958.

PHYSICAL OCEANOGRAPHY

Tidal Currents

Although information on tides for Rhode Island Sound is generally lacking, U. S. Coast and Geodetic Survey Tidal Current Charts show that the ocean tide causes appreciable tidal current oscillations between Rhode Island Sound and the Narragansett Bay system on the north, Block Island Sound on the west and Buzzards Bay and Vineyard Sound on the east.

These currents move in and out of the Narragansett Bay system through West, East, and Sakonnet Passages. The usual maximum flood or ebb surface velocity over the greater part of the Bay is from 0.5 to approximately 1.0 knot. However, in narrow constrictions the surface current is stronger (table 2 and fig. 2).

Non-tidal Circulation

According to Hicks (1959, p. 326), the Narragansett Bay system is a typical two layered tidal estuary with a non-tidal surface flow out of the Bay toward the south and a bottom flow into the Bay toward the north (fig. 7). Hicks also finds that in Rhode Island Sound the non-tidal surface current assumes a westerly drift adjacent to the

TABLE 2.—*Maximum surface tidal currents*[1]

Location	Velocity (knots)
Dutch Island	1.2
Plum Point	0.9
Patience Island	1.0
Bristol Point	1.2
Dyer Island	0.8
Newport Neck	1.5
Tiverton	2.8

[1] After Haight (1938)

Bay mouth and then flows southwest along the shoreline toward Point Judith.

Salinity Distribution

Selected salinity data for Narragansett Bay proper are presented in table 3. These data indicate that the salinity over much of the Bay is generally high. S. D. Hicks (personal communication, 1958) attributes this condition to the relatively small quantity of fresh water which enters the Bay from the Providence and Taunton Rivers and to the absence of intense tidal mixing in the northern portion of the Bay which allows this fresh water to remain on the surface until it is gradually absorbed near the middle of the Bay. As Hicks (1959, p. 324) points out, the salinity of the bottom water is essentially uniform from the middle of the Bay to the head while the surface salinity progressively decreases over the same distance. In addition, lower East Passage is markedly more saline than either West or Sakonnet Passages at both the surface and bottom.

NARRAGANSETT BAY SEDIMENTS

Areal Distribution of Sediments

Based on the gravel, sand, silt, and clay content, eleven sediment types have been distinguished on the bottom surface of Narragansett Bay. These range from the coarsest gravel to clayey silt (fig. 8). It should be pointed out that the term gravel does not necessarily imply inorganic particles but may denote shells and shell fragments. Apparently a predominately clay type is not accumulating on the present bottom.

An examination of the general sediment distribution in the Bay (fig. 8) reveals a rather complex arrangement of these sediments. The finer sediments, sand-silt-clay and clayey silt, characterize the bottoms of the middle and upper parts of the Narragansett Bay system although rather extensive areas of sand are found in upper Narragansett Bay near the head of West Passage. However, at the lower reaches of each passage the sediments become predominately sand types. In the constricted areas, such as near Tiverton, Newport Neck, Bristol Point, and Warwick Point, and along the shoreline of the Bay there is also a tendency toward coarser sediments. In general, upper Narragansett Bay and West and Sakonnet Passages have a greater proportion of their bottom surface areas covered by sand than do either East Passage or Mount Hope Bay. It is noteworthy that sand occurs at a greater distance up the Sakonnet Passage from its entrance than in

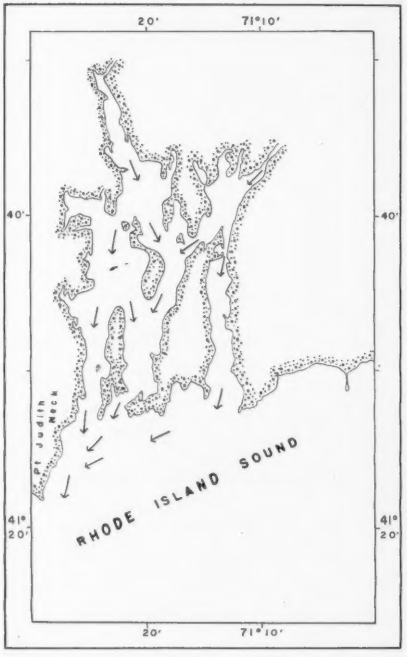

FIG. 7.—Non-tidal surface current pattern for the Narragansett Bay System (adapted from Hicks, 1959, table 2).

TABLE 3.—*Selected salinity observations in the Narragansett Bay system*[1]

Location	Salinity (0/00)	
	Maximum	Minimum
Bay Head (Nayatt Point)		
surface	29.2	23.9
bottom	30.6	27.1
Bay Mouth (West Passage)		
surface	31.3	30.3
bottom	32.3	31.2
Bay Mouth (East Passage)		
surface	32.1	30.8
bottom	32.7	31.7
Bay Head (Fall River, Mass.)		
surface	28.8	15.3
bottom	29.7	23.1
Bay Mouth (Sakonnet Passage)		
surface	31.5	29.9
bottom	31.7	31.3

[1] Adopted from Hicks (1959). Data include all seasons, 1951–1956, and all depth ranges.

any of the other passages. East and Sakonnet Passages show a marked change from finer sediments to coarser sediments over their lower reaches whereas the sediments in West Passage reveal a rapid initial change from sand to clayey silt followed by transition to sand and then back to finer sediment and finally a change toward coarser sediment at the mouth. Toward the south in Rhode Island Sound this coarser sediment again changes to finer sediment.

It is important to note that several areas within the Bay system have served as dumping grounds for dredging operations in the past. These areas are located in East Passage off the southeastern side of Prudence Island, off the southeastern side of Conanicut Island, and around Spar Island, Mount Hope Bay (fig. 3). (U. S. Army Engineers, personal communication, 1958.)

Sand Content

The distribution of sand in the sediments of Narragansett Bay system reflects the same diverse pattern as the sediment types (fig. 9). Sand in quantities of less than 50 percent is found over a large part of the Bay bottom. There are four rather extensive areas in which sand occurs in amounts of less than 25 percent. These are located in upper Narragansett Bay, mid-Bay West Passage, Mount Hope Bay, and the upper part of the Sakonnet Passage. High quantities of sand, greater than 75 percent, are found along the northern and western sides of upper Narragansett Bay, the head and lower part of West Passage near Plum Point, the mouth of East and Sakonnet Passages, and the western edge of the mouth of West Passage. In addition, adjacent Rhode Island Sound shows high proportions of sand in the vicinity of East and Sakonnet Passages, but south of the entrance to West Passage the sand content is much lower.

In certain parts of the Bay system there are areas which show an impressive gradation in sand content over a short distance. For instance, near mid-Sakonnet Passage a marked and complete gradation in sand content occurs in which there is a rapid increase in the amount of sand toward the south. In mid-West Passage a progressive increase in sand is shown over a wide area toward the north, south, and southeast. Gradational areas are also found in lower East Passage and from upper Narragansett Bay toward the head of West Passage.

Clay Content

In the Narragansett Bay system, variable amounts of clay size material occur in the bottom sediments (fig. 10). These amounts range from zero in some samples to as much as 33 percent in others.

Figure 10 shows the clay distribution in the bottom sediments of the Bay system. It is apparent that this distribution of clay lacks uniformity within the confines of the map. Only one area of mappable size contains greater than 30 percent clay; this area is located between Quonset Point and Prudence Island. A significant proportion of the Bay bottom contains sediments with clay contents of greater than 20 percent. Areas with these amounts occur in the more protected middle and upper parts of the system. Extensive areas of less than 10 percent clay are found in the lower reaches of East and Sakonnet Passages as well as along the western edge of upper Narragansett Bay. In contrast, the lower end of West Passage is marked by a tongue of 10 to 20

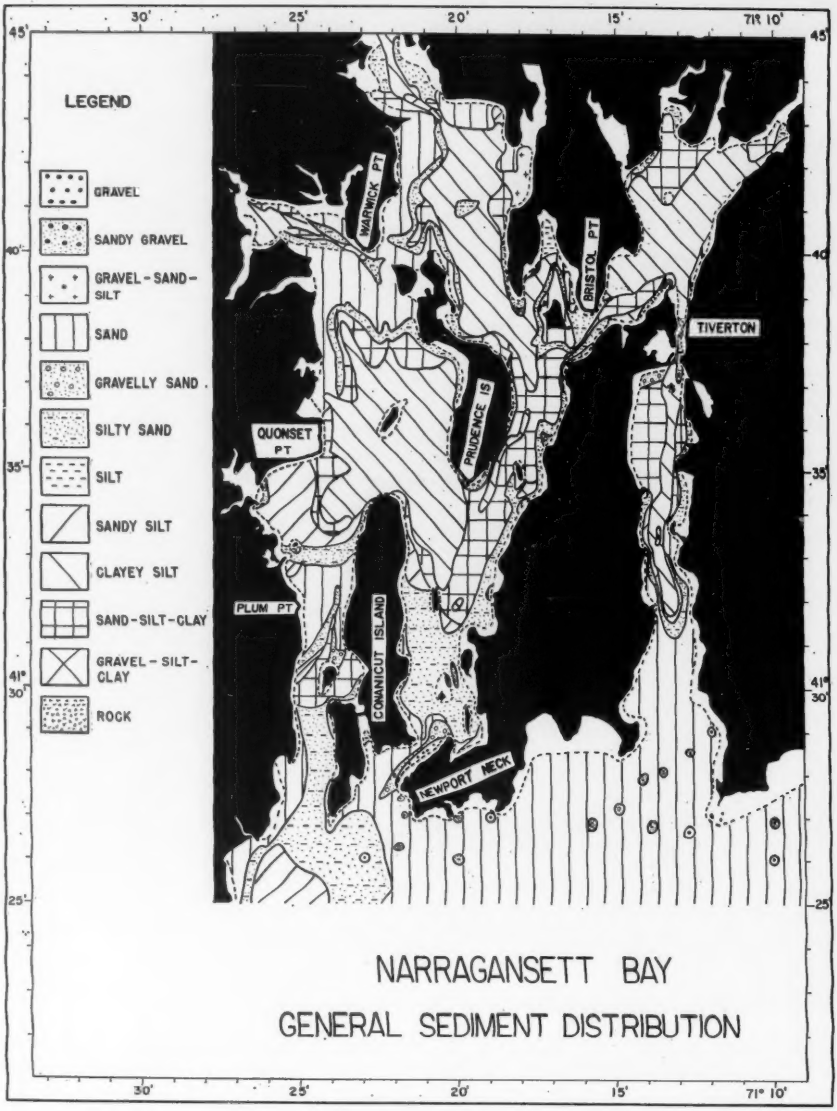

FIG. 8.—Sediment distribution in the Narragansett Bay System based on gravel, sand, silt, and clay content.

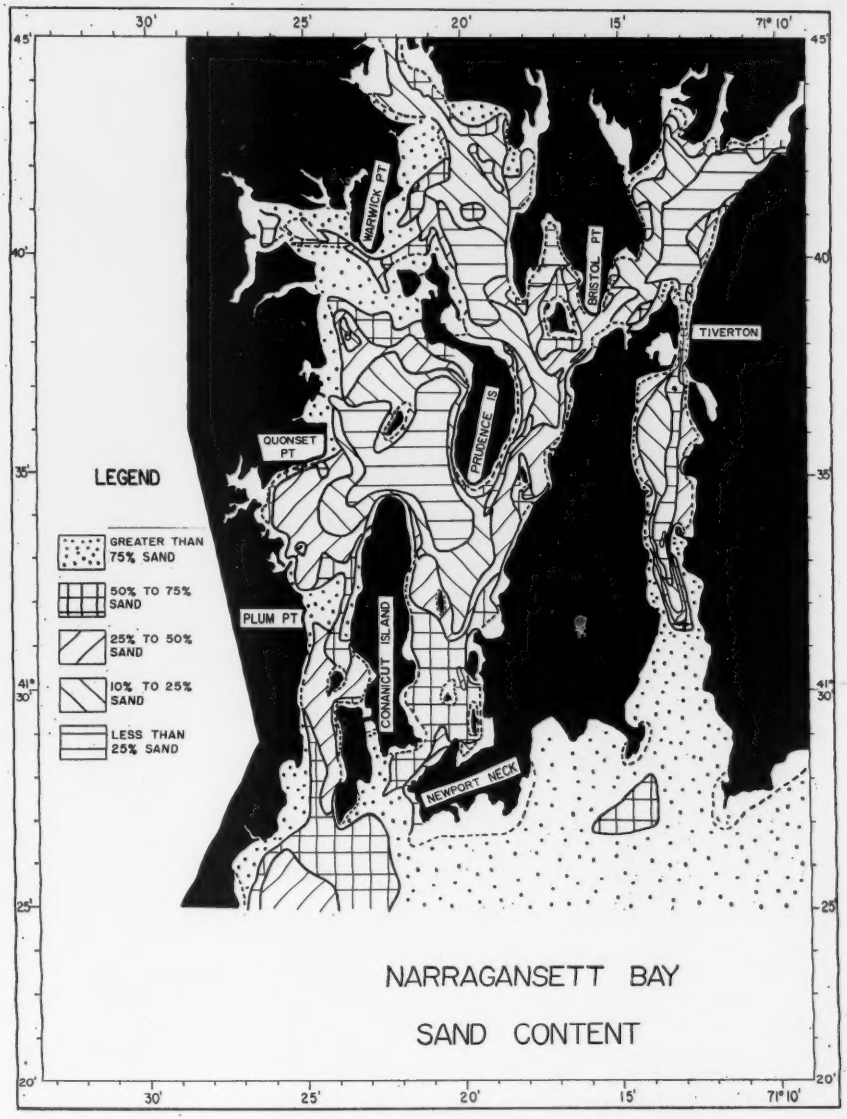

FIG. 9.—Sand content distribution in the Narragansett Bay System.

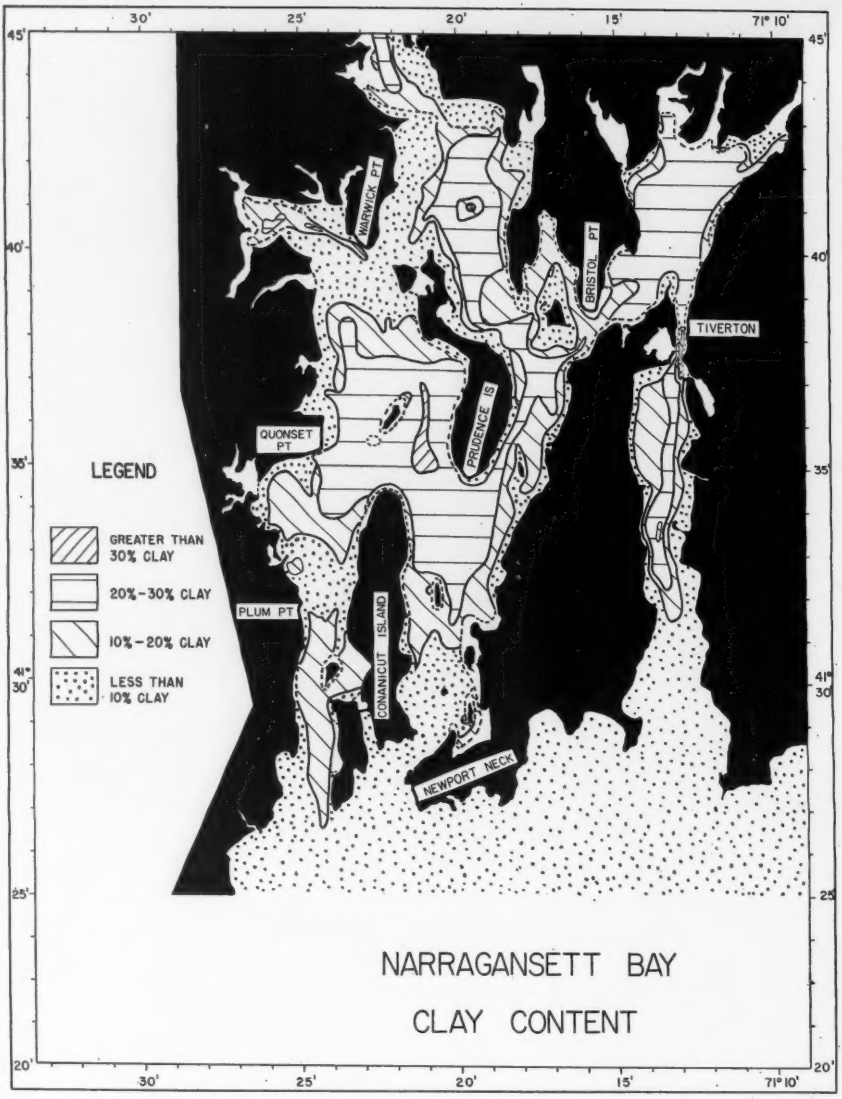

FIG. 10.—Clay content distribution in the Narragansett Bay System.

percent clay which extends to the mouth of the Passage. Apparently the sediments which lie adjacent to the entrances of the three passages contains less than 10 percent clay.

It should be noted that there is also a striking gradation in clay content at several locations. From the middle of West Passage there is a marked decrease in clay toward the north, south, and southeast. A similar change in clay is found near the middle of Sakonnet Passage.

Relative Abundance of Sand and Clay

A plot of the relative abundance of sand and clay is shown in figure 11. This map presents the ratios of percent sand to percent clay in three groups; namely those ratios which are larger than 50 parts sand to 1 part clay (for example, 60:1, 70:1 clay, etc.), those with a 1 to 1 relationship of sand and clay, and those ratios smaller than 1 part sand to 5 parts clay (for example, 1:6, 1:8 clay, etc.).

Areas showing ratios which are larger than 50 to 1 clay are widespread within the confines of the Narragansett Bay system. These are located in upper Narragansett Bay, at the head of West Passage, at several places in lower West Passage, at the mouth of East Passage, and at the lower end of the Sakonnet Passage. In addition, another area of this type is found in Rhode Island Sound immediately south of the entrances to East and Sakonnet Passages.

Sediments containing sand and clay in a 1 to 1 relationship occur as winding belts in upper Narragansett Bay, middle East and West Passages, Mount Hope Bay, near Dutch Island in lower West Passage, and the Sakonnet Passage.

Those areas with ratios smaller than 1 to 5 clay are found in small isolated patches in Greenwich Bay, west of Warwick Point, middle West Passage between Quonset Point and Prudence Island, at the head of East Passage, northwest of Bristol Point, Mount Hope Bay, and middle Sakonnet Passage. Some of these patches contain ratios which are smaller than 1 to 10 clay but only two of these areas, at the head of East Passage and between Prudence Island and Hope Island in mid-West Passage. show any number of low ratio stations (table 4). It is important to note that both of these areas occur in the open Bay.

RHODE ISLAND SOUND SEDIMENTS

Areal Distribution of Sediments and Their Components

Shepard and Cohee (1936, pl. 4) collected a small number of samples within the areas covered by the present paper for Rhode Island Sound and its seaward approaches. Their map of the general type of sediment for the continental shelf off the mid-Atlantic States shows this area to be predominately sand with several large patches of gravel and of sand and gravel lying southeast of Block Island. The northeastern corner of the area in the vicinity of Sakonnet Point is shown to be covered by gravel. Near Sakonnet Point an expanding belt of sand and silt trends toward Block Island Sound to the southwest between Point Judith and Block Island (figs. 1 and 2).

Stetson (1938) and Northrop (1951) also

TABLE 4.—*Areas of low ratio sand to clay abundance*

Location	No. of samples which show a ratio smaller than 1:10 clay	Total no. samples which have smaller ratio than 1:5 clay
West of Warwick Pt. (Greenwich Bay)	—	1
Quonset Pt.—Hope Island	—	5
Prudence Island—Hope Island	6	15
Head of East Passage	6	9
Northwest of Bristol Pt. (Bristol Harbor)	2	2
East side Mt. Hope Bay	3	14
West side Mt. Hope Bay	—	2
Mid-Sakonnet Passage	—	1

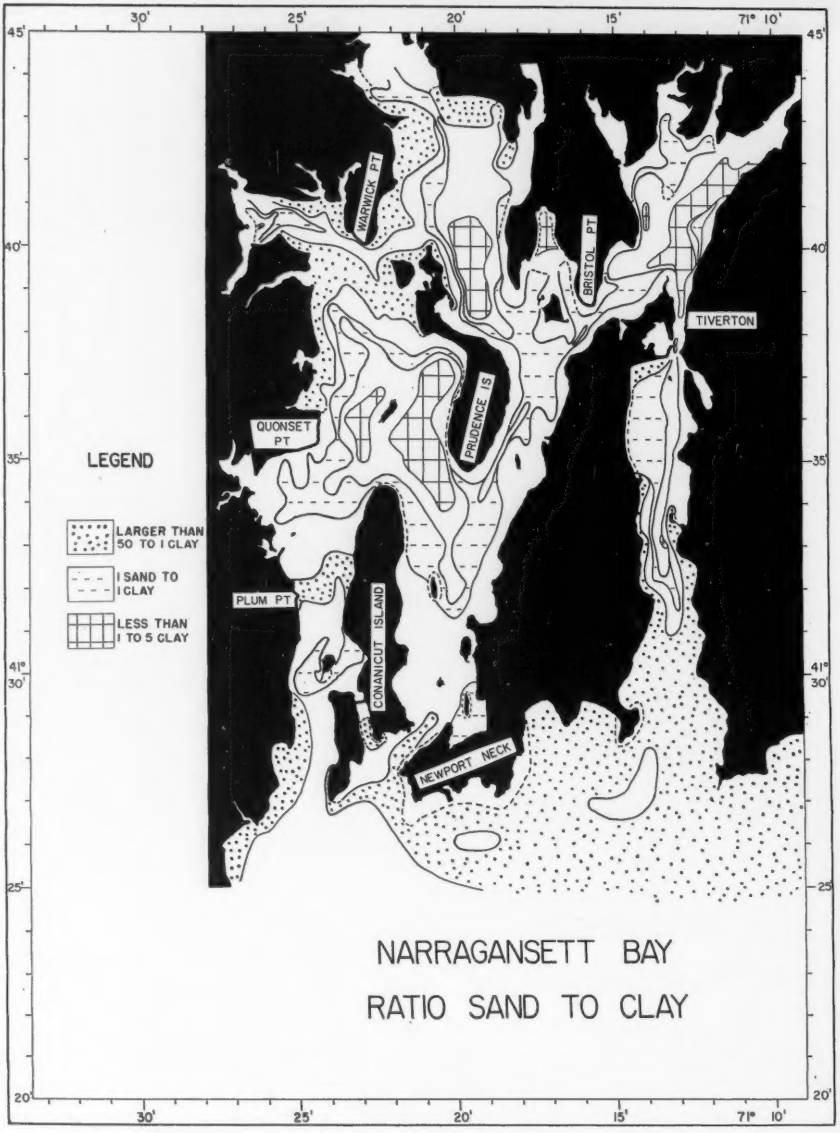

FIG. 11.—Variations in the relative abundance of sand compared with the clay content for the Narragansett Bay System.

studied southern New England shelf sediments and found that these sediments had a distinct distribution pattern. For the inner and middle parts of the shelf Stetson (p. 39) concluded that these sediments begin as a zone of relatively fine, well-sorted sands followed by a belt of coarse sands and gravels, still well-sorted, which in turn is succeeded by a zone of poorly-sorted silts and clays. Northrup (p. 1381) collected a number of closely-spaced bottom photographs and cores along two lines running from the vicinity of Marthas Vineyard (fig. 1) toward the south. His results for the same parts of the shelf show the near-shore end of the traverse to be an area of poorly-sorted gravel which persists 35 miles out to sea into about 264 ft of water. This area, in turn, is followed by a narrow zone, some 10 miles wide, of well-sorted silts and sands and a wide zone of soft mud from 45 to 75 miles off shore.

The arrangement of sediments in Rhode Island Sound and its approaches is shown in figure 12. In general, these sediments are predominately clean sands. The largest area of fine sediment is found adjacent to the Rhode Island mainland just south of the entrance to West Passage. This rather extensive area of fine sediment is composed of a core of sandy silt with less than 10 percent clay surrounded by an irregular mass of silty sand which spreads out from West Passage. Sinuous tongues of this silty sand lead off toward Block Island Sound on the west and Sakonnet Passage on the East. It is interesting to note that a narrow belt of sand lies in shallow depths between these fine sediments and the shoreline; this belt extends toward the north for several miles along the western edge of West Passage before it apparently pinches out.

Over the remainder of the offshore area, isolated patches of coarse and fine sediments are found. However, it should be pointed out that these patches are for the most part the results of a single sample analysis and no attempt has been made to produce larger areas by enclosing similar materials of adjacent samples. This decision was based on the distance between sampling stations and on some field experience in the so-called gravel rich areas. It was found that close interval sampling failed consistently to produce the anticipated sediment type between the normal sample spacings.

Primary grain size analyses suggest that a predominant clay type of sediment is not accumulating within the limits of the offshore area and that clay size material is not even a significant component of the finest sediments within the innermost limits of this shelf location. Apparently the sediment source deposits that are being reworked or were reworked previously either lacked clay or most of the clay was transported outside the region. In addition, what little clay is being removed from the Bay system is carried for the most part beyond the limits of the region before it is deposited.

There is some relationship between bottom configuration and sediment type in this area (fig. 12). For example, the extensive area of fine sediment which is located near Point Judith lies along the base of the curving western slope of the semi-basin which is found adjacent to the entrances to East and West Passages. The irregular tongue of silty sand leading toward the southwest follows the base of this curving slope westward toward Block Island Sound.

The submarine trunk valley which crosses the area from the northeast toward the southwest in the vicinity of latitude 41°21′N and longitude 71°W contains several patches of fine sediment (fig. 12). The larger patch, located at the eastern edge of the area, lies at the junction of valleys leading toward Buzzards Bay to the north and Vineyard Sound to the northeast. Small patches of fine sediment are also found at two locations in the trunk valley near the deeper depths toward the southwest.

Figure 13 shows the locations of offshore samples which contain greater than 10 percent gravel. From this distribution plot it is obvious that significant amounts of gravel are not uniformly disseminated throughout the area but rather suggest local concentrations. These groupings appear to be confined within rather narrow belts which can be readily traced across the Sound and its seaward approaches (J. P. Schafer, personal communication, 1958; fig. 6). One of these belts extends from the vicinity of Point Judith toward the southeast and then bends back in a northeasterly direction toward the edge of the area. It is interesting to note

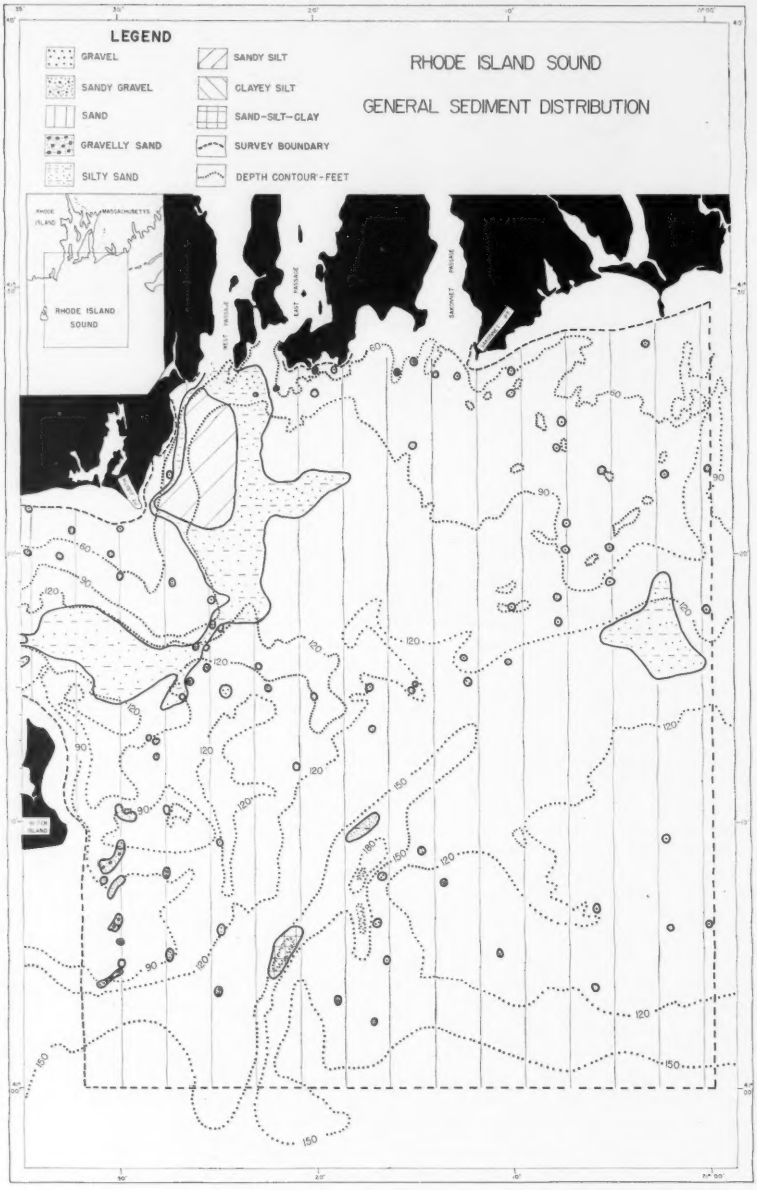

FIG. 12.—Sediment distribution in Rhode Island Sound based on gravel, sand, silt, and clay content.

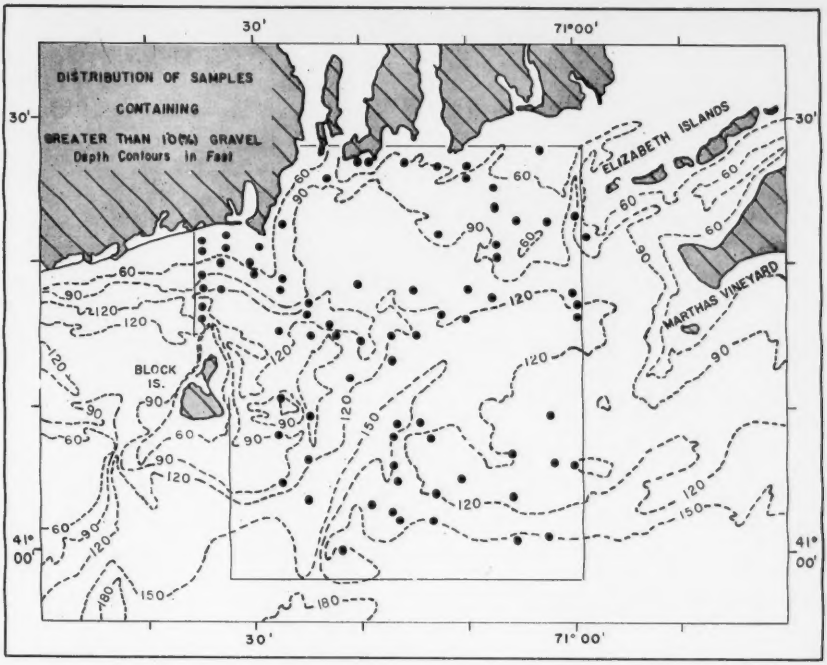

FIG. 13.—Location of sediment samples containing greater than 10 percent gravel in Rhode Island Sound and its approaches.

that a secondary trend develops near the entrance to Sakonnet Passage which follows a southeasterly direction thereby joining the main belt near the edge of the area.

Another belt of gravel concentration crosses the area near the southern limits of the map (fig. 13). This belt is broader than the one to the north and has a more easterly trend. Undoubtedly this belt of gravel concentration is linked to Stetson's (1938, p. 13) zone of coarse, well-sorted sands and gravels and Northrop's (1951, p. 1381) gravel area.

SOURCES, TRANSPORTATION AND DEPOSITION OF SEDIMENTS

In previous studies of sediments of the continental shelf off the eastern coast of the United States Shepard and Cohee (1936, p. 452) and Stetson (1938, p. 36) recognized that the rivers along the coast are of practically no importance in supplying sediment to the shelf at present. With specific reference to the New England shelf, Stetson (p. 36) concluded that (1) since these streams carry very little sediment in suspension, what little there is must be effectively trapped by the deep basin of the Gulf of Maine and by Long Island Sound and (2) the source of these present day sediments, therefore, is largely reworked glacial debris of the Wisconsin ice. This latter conclusion is also shared by Northrop (1951, p. 1383).

Although it has been recognized that a relatively small quantity of fresh water flows into the Bay from the Providence and Taunton Rivers (S. D. Hicks, personal communication, 1958), unfortunately there are no data available concerning the sediment loads for these streams or other streams entering the Narragansett Bay system.

However, it is believed that the greatest proportion of sediment carried by the fresh water discharge never reaches the confines of the Bay. As pointed out by C. E. Miller (personal communication, 1958) streams of the Narragansett Bay region have abnormal gradient characteristics since most of their channels are partially blocked by natural or artificial dams at one or more points. In effect, this condition produces a number of settling basins along the stream courses thus depriving the streams of their normal sediment load. In addition, the lower reaches of the Providence and Taunton Rivers, which contribute the greatest volume of runoff to the Bay system, are favorable locations for fine sediment deposition because of the presence of saline bottom waters in these estuaries (fig. 2, table 3). Therefore, it is assumed that the sediment load entering the Narragansett Bay system by stream flow is small even though this quantity may vary somewhat with the precipitation and runoff.

Based on the texture of the finest sediments of the Bay bottom surface, it is also inferred that the sediment load in the Bay is composed of some fine and very fine sand, silt and clay size particles. This material is derived essentially from subaerial glacial deposits in the surrounding watershed areas. Some additional sediment is produced during times of severe storms by erosion of unconsolidated glacial and post-glacial deposits which occur along the Bay shoreline in many areas. In addition since glacial deposits covered the present Bay and Sound floor, the waves and currents of the transgressing seas have reworked and continue to redistribute certain lag textural components of these deposits which come within range of their effectiveness (Stetson, 1938, p. 37). It is believed that the consolidated rocks which crop out at the shoreline contribute little if any appreciable amount of sediment.

Although the sediment types found on the bottom surface of the Bay and Sound reflect present environmental influences, as Stetson (1938, p. 38) has suggested, it should be emphasized that these present surface sediments actually represent erosion cycles of differing complexity. In the Bay this condition is quite apparent from the arrangment of sediment types (fig. 8). For example, some of the fine detritus was derived from the surrounding watershed areas and was carried into the Bay by streams. Other fine material was obtained from the reworking of older Bay floor deposits by waves and currents. A large proportion of this fine sediment was deposited over or mixed with the older glacial sediments at favorable localities. However, there are some sediment types on the bottom surface that represent the unburied lag constituents of these older glacial deposits as determined by present current activity. The location of these reworked deposits is controlled by underwater relief and shoreline configuration since these lag deposits occur where bottom agitation is at a maximum since this condition is the result of constricted flow or shallow depths or both. In describing the sediment distribution on the continental shelf off the New England coast, Stetson (1938, p. 38) implied a similar relationship of surface sediment types.

In the Bay region there are a number of factors which control the location of the fine sediment depositional areas. Some of these are (1) current velocities and turbulence which are affected by the configuration of the shoreline, submarine topography, and bottom roughness, (2) non-tidal drift, (3) salinity and density characteristics of the water mass, and (4) nature and concentration of the sediment load which varies with discharge and severe storms.

During the effective period of present environmental conditions these variables have permitted the fine sediments to accumulate for the most part in certain areas in the middle and upper parts of the Bay system (figs. 8, 9, 10, and 11) even though the mechanics of the process are not understood. For example, these sediments apparently are accumulating in the channel of the lower Providence River and upper Narragansett and Mount Hope Bays associated with the channel areas along their eastern sides. In addition, other areas occur in mid-Bay East and West Passages and the upper Sakonnet Passage.

It is interesting to note that the finest composite material in the Bay system is apparently settling in small areas in Greenwich Bay, west of Warwick Point, mid-Bay

West Passage, at the head of East Passage, Mount Hope Bay, and mid-Sakonnet Passage (fig. 11). It is possible that the peculiarities of tidal current flow may be related to the location of these sediments. Recently the U. S. Army Corps of Engineers (personal communication, 1958) photographically recorded model studies of the surface pattern of tidal current flow for the Narragansett Bay system. Unfortunately, data from these studies are available only for Narragansett Bay proper and not for Mount Hope Bay or the Sakonnet Passage. Although it is recognized that these model studies may have limited application to true field conditions of water mass circulation, certain observed surface current patterns suggest a close relationship with several areas of finest deposition within Narragansett Bay proper. For example, the model records reveal that the Bay waters off the southwestern side of Prudence Island adjacent to Hope Island as well as the waters off the northeastern side of Prudence Island at the head of East Passage are slack for about three hours during each tidal cycle. Since these locations roughly coincide with the areas of finest sediment, it is possible that these surface current conditions influence the type of sediment accumulating on the Bay floor in these areas. It is also evident (table 4) that in the open Bay these same areas have the largest number of the lowest sand to clay ratio stations.

The depositional areas of the finest sediments are bordered by belts of sediments which grade toward coarser sediment types although the degree and magnitude of transition vary considerably (figs. 8, 9, and 10). The most striking examples of transitional zones are found in mid-West and mid-Sakonnet Passages. It is believed that these gradational zones and others within the Bay system indicate significant local changes in current activity along the bottom interface.

In general, toward the lower reaches of the Bay passages the bottom sediments show a gradual change toward coarser textured material. This pattern of sediment distribution is probably related to the occurrence of tidal induced turbulence near the entrances to the Bay system (Haight, 1938) which progressively reduces the amount of suspended sediment allowed to reach the bottom.

Since finer sediments are found in close proximity to the mouth of West Passage, bottom current agitation is probably less severe in the lower reaches of West Passage than in either East or Sakonnet Passages. This inference seems to be borne out by several conditions. S. D. Hicks (personal communication, 1958) suggests, on the basis of his unpublished data, that there is a significant eddy pattern around Dutch Island in the lower part of West Passage. In all probability this eddy effect is responsible for the local accumulation of fine sediment in the vicinity of Dutch Island (figs. 8, 9, and 10). Since the mouth of West Passage is somewhat protected by the adjacent extension of mainland toward the south and since the general circulation pattern in Rhode Island Sound moves across the passage entrance and then southward along the mainland, these conditions certainly affect normal current activity in the lower reaches of the Passage.

The fact that clean, well-sorted sands occur in the lower reach of the Sakonnet Passage merits consideration (figs. 8, 9, and 10). Although there are undoubtedly several factors which are responsible for this condition, shoreline configuration, shallow water depths, and exposure to the open sea collectively promote sufficient turbulence at the bottom to keep this area free of fine sediment.

If some of the sediment load escapes these catch basins in the Bay system, especially at times of heavy discharge or runoff or after severe storms, the course of surface non-tidal drift concentrates this sediment load adjacent to Point Judith Neck (fig. 7). Here some deposition takes place primarily in the form of silt (fig. 12). From this area, the depositional belt extends toward the southwest and Block Island Sound. If clay size material is a significant part of the suspended load which reaches the open water, it is carried beyond the limits of the study area.

It is not believed that outflow transports all the sediment that reaches the various parts of the Bay system and the shelf. For example, along the western side of Rhode Island Sound and West Passage there is

conclusive evidence that the predominant littoral drift in the area moves toward the north (U. S. Congress, 1950, p. 19) even though this inshore drift is opposed to the general southerly counter-clockwise current pattern in upper Rhode Island Sound (fig. 7). Apparently this northerly moving inshore current is responsible for the tongue of sand which is found adjacent to the mainland from Point Judith into lower West Passage (figs. 8 and 12). As Johnson (1956, p. 2223) points out, turbulent forces created by surface waves seaward of the breaker zone apparently are sufficient to cause a general longshore movement of sand out to depths as great as 60–80 ft.

In general, on the inner shelf areas of Rhode Island Sound the absence of fine detritus is due primarily to the lack of a sizeable quantity of transported sediments from the Bay system and the coastline. Even the small amount of sediment load that is available is kept essentially clear of the bottom by normal water mass turbulence. There may be some deposition going on in the submerged valley which cuts across the Sound from northeast to southwest (fig. 12) as indicated by the patches of fine sediments. In all probability these sediments have been flushed from Buzzards Bay.

CONCLUSIONS

General

1. The major submarine topographic features of the Narragansett Bay system and Rhode Island Sound are primarily the product of previous environmental conditions rather than the result of present environmental forces.
2. Preliminary evidence suggests that prior to the glacial period three major trunk channels drained the present Narragansett Bay system lowland. These buried valleys follow the general trend of West, East, and Sakonnet Passages.
3. Although a number of sediment types have been found in the study area, neither the Bay system nor the inner shelf contain a predominant clay type of sediment. In addition, clay size material is not even a significant component of the finest composite sediment within the innermost limits of Rhode Island Sound.
4. In the Bay system and certain areas on the inner shelf unburied lag deposits of glacial or post-glacial origin juxtapose with recently accumulated fine sediments.
5. From the study of sediment distribution it is evident that in the Bay system depositional processes under recent environmental conditions have had the greatest success in covering sedimentary deposits of previous environments.

Narragansett Bay System

1. Fine detritus, clayey silt and sand-silt-clay collectively, has the greatest distribution on the bottom surface although areas of sand are important locally.
2. Sediments are primarily derived from subaerial glacial deposits in the watershed areas, shoreline unconsolidated glacial and post-glacial materials, and subaqueous glacial deposits.
3. It is believed that within the Bay system the quantity of sediment available for deposition from all sources is very small. Essentially this sediment load is composed of some fine and very fine sand, silt, and clay.
4. During the effective period of present environmental conditions, fine sediments, clayey silt and sand-silt-clay, have accumulated for the most part in the more protected middle and upper area of the Bay system. Apparently the finest of these composite sediments are being deposited at a number of small localities within these areas. Deposition of this finest detritus seems to have a close relationship with the peculiarities of surface tidal current flow although other factors may be involved.
5. Within the Bay system the areas which show marked gradational changes in sediment textural characteristics probably indicate significant local variations in current activity along the bottom interface.
6. In general, toward the lower reaches of the Bay passages, the bottom sedi-

ments show a progressive change to coarser textures. This pattern of sediment distribution is probably related to the occurrence of tidal induced turbulence which reduces the amount of suspended sediment allowed to reach the bottom toward the entrances of the Bay. Near the mouth of West Passage, the gradation toward coarser material is less noticeable because of the modifying effect of the non-tidal current pattern in upper Rhode Island Sound and only partial exposure to the open sea. However, the magnitude of the areal extent of clean, well-sorted sand in lower Sakonnet Passage is probably the result of the additive effect of shoreline configuration, shallow water depth, and exposure to the forces of the open sea.

Rhode Island Sound and Its Approaches

1. The predominant sediment is clean, well-sorted sand.
2. If some of the sediment escapes the catch basins in the Bay system, the course of non-tidal drift concentrates this sediment load adjacent to Point Judith Neck. Here some deposition takes place in the semi-basin near the entrances to West and East Passages. This depositional material consists primarily of silt, a lesser amount of sand, and a small proportion of clay. From this area the depositional belt follows the general trend of a winding submarine slope toward the southwest and Block Island Sound.
3. If clay size material is a significant part of the suspended load which reaches the open water, it is carried beyond the limits of the study area.
4. In general, the scarcity of sediments reaching the shelf coupled with the efficacy of bottom current activity on the inner shelf have kept deposition from inland sources restricted to certain well-defined areas within the Sound.
5. Apparently the tongue of sand that is found adjacent to the Rhode Island mainland from Point Judith into lower West Passage owes its origin to a northerly moving current which pushes into the Bay from Block Island Sound.
6. The available gravel is concentrated to a great degree along two major trends. Generally, these trends are associated with the two submarine elevation features which cross the area.

ACKNOWLEDGMENTS

The sediment data used in this report were taken from the files of the Narragansett Marine Laboratory. The original studies which provided these data were made possible through the financial support of the Office of Naval Research (Contract Nonr-396(01) and the U. S. Army Corps of Engineers, Office of the Division Engineer, New England Division (Contract DA-19-016-CIVENG-56-1071). Sincere appreciation is expressed to J. J. Donohue, L. E. Garrison, I. A. Canty, C. G. Hard, G. E. Brayton, and D. E. Frazier for their invaluable contributions in the field and laboratory investigations. Special thanks are due C. E. Miller, J. S. Kahn, D. M. Pratt, and J. P. Schafer who kindly read the text and made many helpful suggestions. A University of Rhode Island Research Grant-in-Aid which provided funds for drafting services is gratefully acknowledged.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 30, NO. 2, PP. 275–282
FIGS. 1–3, JUNE, 1960

CROSS SECTION OF A FLOODPLAIN IN A MOIST REGION OF MODERATE RELIEF[1]

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ABSTRACT

The cross section of a small floodplain in the Appalachian Plateau was shown in excavations and borings for a dam. Deposits of vertical accretion, lateral accretion, lag deposits, channel fill, and colluvium fill the valley of an aggrading stream. Colluvium comprises almost one fifth of the total valley fill and contains isolated lenses of vertical accretion. The colluvium built out from the valley side as the stream shifted laterally across the floodplain. Vertical and lateral accretion deposits may be sharply differentiated where exposed in a trench; the lateral accretion is composed of 70–75% sand size material and the vertical accretion of 35–60% clay size material.

INTRODUCTION

Drilling and excavations for a dam across a stream in the Appalachian Plateau of Pennsylvania gave considerable local information on the floodplain deposits. As the excavations and bore holes were primarily confined to the axis of the dam, the information revealed the characteristics of a cross section of the floodplain.

A cross section of Beaverdam Run, Cambria County, Pennsylvania, was studied at the site of Glendale Dam (lat 40°41.9′N; long 78°32.2′ W) approximately 13.5 miles north northwest of Altoona (fig. 1). This area is shown on the 15-minute Patton, Pennsylvania topographic quadrangle.

Beaverdam Run drains an area immediately west of the Allegheny Topographic Front and hence wholly within the Appalachian Plateau. The drainage basin has a local relief of about 240 ft and consists of rolling to flat uplands constituting about 8 percent of the area projected onto a horizontal plane, slopes of 3.5 to 6 degrees and averaging 4.5 degrees, and valleys ranging from v-shaped to those with floodplains approximately ½ mile wide.

The annual average rainfall is 39 in and is rather uniformly distributed throughout the year. The largest monthly precipitation, approximately 4 in, occurs in June and July. In March, 1936, 4.1 in fell in 24 hours, and during the spring of that year the river was out of its banks for six consecutive days.

[1] College of Mineral Industries Contribution Number 58–59. Manuscript received September 21, 1959.

GEOLOGY

Rocks of the Allegheny and Conemaugh Series of Pennsylvanian age underlie the drainage basin. These rocks are interbedded sandstones, siltstones, shales, limestones, underclays, and coals. Some thin lenses of conglomerate occur. Volumetrically, by far the most important constituent of these rocks is quartz in the fine sand and coarse silt sizes, 0.04 mm to 0.2 mm (E. G. Williams, personal communication). The bed-

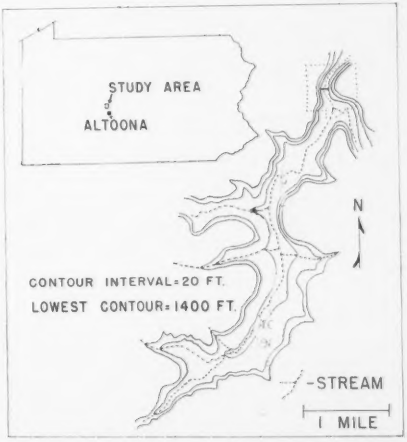

FIG. 1.—Location map and general topography of the valley of Beaverdam Run. The area shown in detail on figure 2 is included within the dotted line at the north end of the valley. The cross section studied is indicated by the heavy line across the valley within the area outlined by the dotted line.

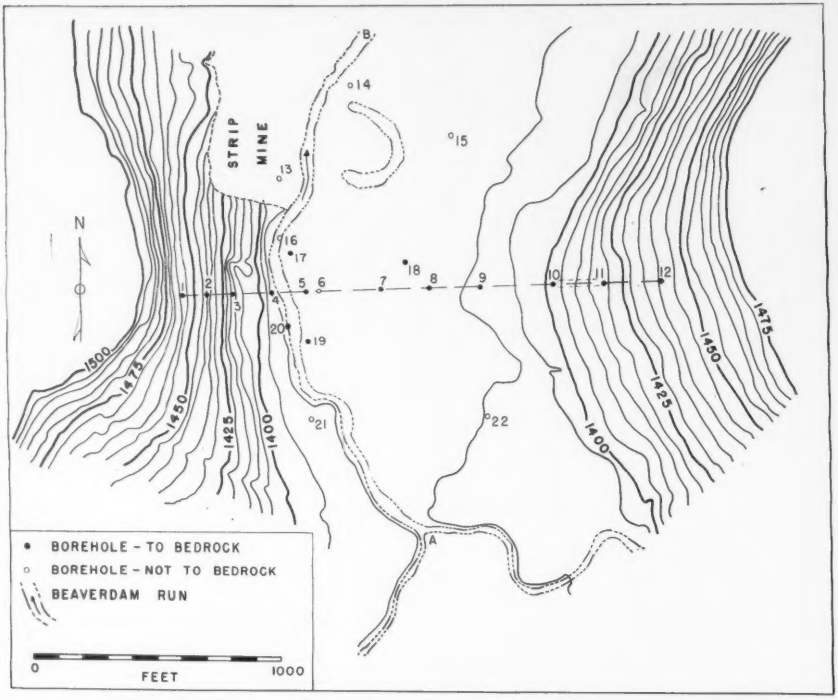

FIG. 2.—Topography in the vicinity of the cross section. The position of this map is shown by the dotted line on figure 1. The cross section studied extends from borehole 1 to borehole 12.

ding throughout the region dips gently and at the dam site dips to the south at about 1°.

The drainage basin of Beaverdam Run is south of the limit of Pleistocene glaciation and contains no proglacial deposits.

Beaverdam Run

Beaverdam Run is a permanent stream that flows northward to Clearfield Creek and eventually to the West Branch of the Susquehanna River. Upstream from the dam site Beaverdam Run is approximately 9 miles long and with its tributaries drains an area of 42 square miles. For several miles south of the dam site, the valley is about ½ mile wide (fig. 1) and has a local relief of approximately 20 ft. At the dam site the valley is constricted (fig. 1), and the alluvium at the surface is about 850 ft wide (fig. 3A).

At the cross section studied (fig. 2), Beaverdam Run is 40 to 50 ft wide and at bankfull stage is 4 to 4.5 ft deep. Referring to figure 2, the bed of the stream at A is at 1381.4 ft, at the dam site (cross section) it is at 1380.7 ft, and at B it is at 1381.1 ft. Thus, the gradient of the stream is irregular and drops 0.3 ft from A to B with an average gradient between these points of less than one foot per mile. There are no visible nickpoints in the stream between A and B (fig. 2).

Although the stream is not now meandering in the vicinity of the cross section, at least one cutoff meander containing standing water occurs approximately 500 ft north of the cross section. Beaverdam Run overflows its banks at least once each spring and commonly four or five times a year.

CROSS SECTION OF BEAVERDAM RUN

Description of Cross Section and Vicinity

The topography in the vicinity of the dam site cross section is shown on figure 2. The slopes rise from the floodplain at about 5.5° to a height of 120 ft and then extend at about 3.5° for 110 ft to the uplands which are therefore 230 ft above the floodplain. The valley is approximately 1¼ miles wide between the opposite divides.

Eleven bore holes to bedrock were drilled along an east-west cross section 1940 ft long (bore holes 1 to 5, 7 to 12 of fig. 2). Of these, six holes (4, 5, 7, 8, 9, 10) penetrated alluvium, outlining an alluvial valley approximately 1250 ft wide (fig. 3A). Cores and logs of all bore holes were available.

A core trench approximately 40 ft deep and 25 ft wide was dug to bedrock at the eastern edge of the alluvial valley (fig. 2, cross-hatched area between bore holes 10 and 11, figs. 3A and B) and extends westward from the buried valley wall for approximately 150 ft. The section in this trench was completely exposed in both walls.

Configuration of the Bedrock Valley Floor

Except for continuous exposure in the core trench, the position of the bedrock floor of the alluvial valley is known only from bore holes. In addition to the six bore holes which reach the valley floor along the cross section, bore holes 17, 18, 19, and 20 (figs. 2 and 3A) reach bedrock, and bore holes 13, 14, 15, 16, 21, and 22, while not reaching bedrock, give a minimum possible distance to bedrock.

The sparse bore hole data allow only an approximation of the configuration of the bedrock floor. The data indicate (fig. 3A) that the floor is highest in the center, lower on the west side, and lowest on the east side.

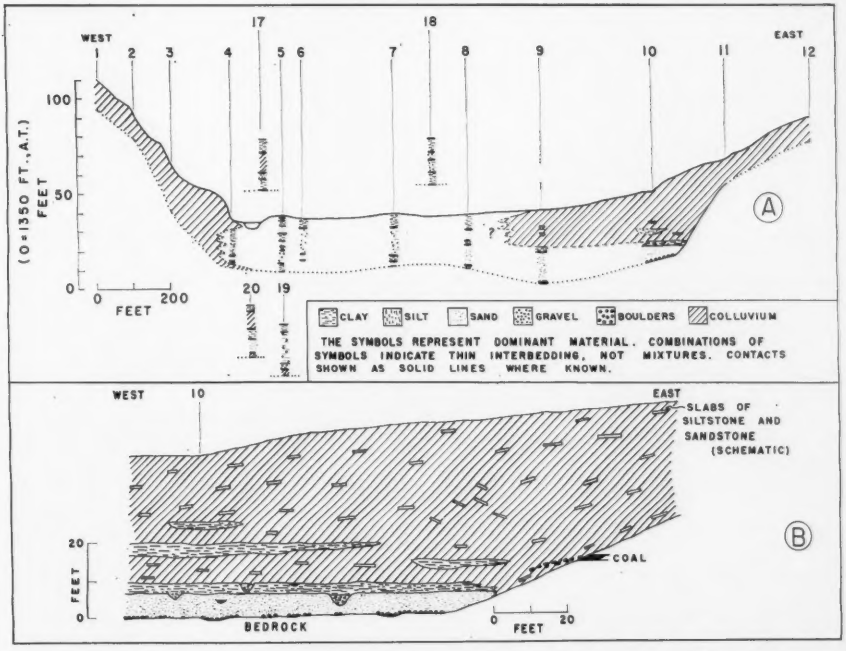

FIG. 3.—Cross sections of floodplain and core trench. 3 A.—Cross section of floodplain; 3 B.—Cross section exposed in core trench. Legend applies to both cross sections.

The highest part in the center is about 12 ft higher than the lowest part on the east side.

The bedrock floor in the core trench has a local relief of about 1 ft consisting of gentle sags (fig. 3B). The floor of the trench slopes uniformly down toward the west at about 1 ft in 90 ft.

The buried valley wall on the east side is shown in the core trench and at several exposures in excavation parallel to the valley edge. This wall slopes at about 22° wherever seen. The exact position and slope of the buried west valley wall is unknown.

Bore hole 21 bottoms in alluvium at 1361 ft above sea level, bore hole 22 bottoms at 1357 ft, bore hole 14 bottoms at 1356, and bore hole 15 bottoms at 1360 ft. The general elevation of the bedrock floor along the cross section is between 1350 and 1360 ft. This information, and data from other bore holes not indicated on the map, indicates that any longitudinal slope of the bedrock floor in the vicinity of the cross section is too slight to be detected by the available data.

Description of Deposits in the Alluvial Valley

The deposits in the alluvial valley (between bore holes 4 and 11, fig. 3A) are very heterogeneous. The bore hole records describe deposits of clay, silty clay, sandy clay, sandy silt, silty sand, sandy gravel, sand, and boulders. Figure 3A shows the position of these deposits where actually known. Despite the variability of the material in the alluvial valley, it is possible to distinguish five basic types: colluvium, lag deposits, channel fill deposits, lateral accretion, and vertical accretion, which have been described by Happ, Rittenhouse, and Dobson (1940).

Colluvium.—The colluvium in the alluvial valley consists of angular slabs of siltstone and sandstone from 1 to 4 in thick and from 2 in to 2 ft in long dimension in a matrix of yellow silty clay. All types of material in the colluvium are present in the underlying bedrock. Fragments of wood of all sizes are common.

The colluvium is 6 to 10 ft thick on the slopes above the floodplain (fig. 3A) and forms a thick wedge in the eastern part of the alluvial valley. Above the buried east valley wall the colluvium is about 40 ft thick and extends westward for approximately 500 ft into the valley. On the west side of the valley thin tongues of colluvium underlie and overlay the alluvium (bore hole 4, fig. 3A) in the cross section. North and south of the cross section (bore holes 17, 19, 20) colluvium makes up an important constituent of the valley fill and in bore hole 19 is seen to be present at least 100 ft east of the present stream position.

Detailed study of the colluvium was possible in the core trench at the east edge of floodplain (fig. 3B). The slabs of siltstone and sandstone are parallel to the surface of deposition in the lower part of the section and apparently parallel to the surface of deposition throughout the section in the trench. Locally, masses of the colluvium exhibit slabs all dipping back into the slope and indicating that, at least locally, slumping has played a part in the implacement of colluvium in the valley fill. Low in the valley wall is a 2-ft thick bed of coal (fig. 3A), and detrital coal from this bed extends outward approximately 20 ft in an undisturbed layer.

Within the thick colluvium in the trench are several lenses of silty clay or vertical accretion (see below) up to 5 ft thick. They are discontinuous perpendicular to the cross section because the easternmost lens shown in figure 3B is visible in the north wall of the trench but is not present in the south wall approximately 25 ft away.

The colluvial wedge on the east side of the floodplain is approximately 20 ft thick in bore hole 9 (fig. 3A) and absent in bore hole 8 approximately 200 ft to the west, so the wedge may thin quite rapidly.

Lag deposits.—Lag deposits are the coarsest material on the channel bottom and have been winnowed of finer material.

The coarsest material in the floodplain consists of boulders up to 1 ft in diameter forming a thin 1-ft thick, discontinuous layer resting directly on bedrock and exposed in the trench and as far west as bore hole 9. These boulders are considered part of a lag deposit. They are coarser than any material now exposed in the bed of Beaverdam Run.

The layer of lag deposits in the trench consists of material ranging from coarse sand (1.0 mm) up to the boulders. All of the detritus is sub-rounded to rounded and is unweathered. The boulders are sandstone, silt-

stone, and limestone, all indigenous to the drainage basin.

The bedrock floor of the trench has a relief of about 1 ft, and the largest lag material is found in sags in the floor approximately 1 ft deep and 5 to 10 ft wide. All of the lag material is found in the eastern part of the bedrock valley floor.

Channel fill.—Several filled channels are exposed in the walls of the trench (fig. 3B). The channels are of various sizes up to approximately 5 ft deep and 5 ft wide at the top. They occur in the sand at the bottom of the trench and in the overlying clay, and some cut both the clay and sand. No filled channels were found extending into the colluvium or wholly within the colluvium.

The channels in the trench are all filled with poorly sorted silt, sand, and gravel; only a trace of clay-size material is present. The coarsest material found was well-rounded gravel up to 3 inches in longest dimension. A common constituent of the channel fill is wood of various sizes up to pieces 3 in thick and approximately 12 in long. Some of the wood had apparently been burned before deposition. Field examination revealed no trace of bedding of any type in the channel fill in a two-dimensional view.

Some of the alluvium penetrated by the bore holes west of the trench and shown on figure 3A as gravel and sand and gravel, are also probably channel fill, but the exact extent of these channels cannot be determined.

Lateral accretion.—Lateral accretion is apparently always an important constituent of a floodplain and may constitute almost the entire floodplain (Fenneman, 1906). Lateral accretion, or point bar deposits, are believed by Wolman and Leopold (1957) to be the major constituent of floodplains.

The material indicated as sand on figure 3 is interpreted, for the most part, as lateral accretion. This sand is well exposed as a layer approximately 6 ft thick in the core trench where it directly overlies the lag gravel or bedrock floor. At the eastern valley wall, the sand interfingers with colluvium.

Seven samples of the sand taken at random from the trench show a very uniform grain size distribution (table 1). The material is buff-colored and consists of 70 to 75% sand, 20 to 25% silt, and only 1 to 5% clay. The largest fraction, 30 to 35%, is fine sand (between 0.125 mm and 0.250 mm). The median sizes of the samples range from 0.141 mm to 0.147 mm and average 0.145 mm. The predominant and median sizes of the lateral accretion accord closely, therefore, with the predominant size of the quartz grains in the bedrock discussed previously. The average Trask sorting coefficient is 1.67. Fragments of wood, some apparently burned, occur commonly throughout the lateral accretion in the trench and are from fragments visible only under 10 power magnification to pieces up to ½-inch in longest dimension. Some wood fragments are well rounded. Isolated, well-rounded pebbles from ⅛ to ½ inch in diameter occur very widely scattered throughout the sand.

TABLE 1.—*Comparison of lateral and vertical accretion exposed in core trench*

COMPARISON OF LATERAL AND VERTICAL ACCRETION IN TRENCH		
SIZE	LATERAL ACCRETION	VERTICAL ACCRETION
ALL MATERIAL IS LESS THAN	1.0 MM.	0.42 MM.
% SAND 0.062–2.0 MM.	70–75 %	5–10 %
% SILT 0.0039–0.062 MM.	20–25 %	20–40 %
% CLAY < 0.0039 MM.	1–5 %	35–60 %
MEDIAN SIZE	0.145 MM.	VERY VARIABLE
SORTING $\sqrt{\frac{Q_3}{Q_1}}$	1.67	(SEE TEXT)

The layer of lateral accretion in the trench has a very uniform thickness although its upper contact (with the overlying clay) is irregular and has 6 to 8 in of relief. No bedding of any type was seen in the field by several observers, nor is any thin bedding apparent apparent under 40 power magnification. The deposit in the trench is massive.

Alluvium indicated as sand on figure 3A in the bore holes west of the trench (note especially bore holes 8 and 9) is interpreted as probable lateral accretion.

Vertical accretion.—Vertical accretion, or overbank deposits, are the finest-sized ma-

terial in a floodplain. The material indicated as predominantly clay in figure 3 is interpreted as vertical accretion.

In the core trench (fig. 3B) a layer of grey to buff clay about 2 ft thick directly overlies the lateral accretion and is overlain by colluvium. The upper and lower contacts of the clay layer are somewhat irregular, but the layer has a rather uniform thickness, and the contacts are sharp and easily observed. The clay interfingers with colluvium near the buried valley wall. Lenses of clay (vertical accretion) occur in the colluvium and also have sharp, clearly marked contacts. No lateral accretion is associated with the vertical accretion lenses in the colluvium.

The size distribution of the vertical accretion is very variable, but all of the material is finer than medium sand (table 1). Although most of the material is in the clay size range, silt is always an important constituent and may comprise almost 50 percent by weight of the vertical accretion.

Samples of vertical accretion were taken from the clay layer above the lateral accretion in the trench, the lenses in the colluvium, and the present surface of the floodplain. The clay-size material in all samples is primarily illite and kaolinite. The areas ununder the illite (10Å) and kaolinite (7Å) peaks on the diffraction traces are about equal. Degens, Williams, and Keith (1958) report that the bedrock shales (Freeport Shales) of the drainage basin are illite and kaolinite and that the areas under the peaks are about equal. Therefore, the clays of the vertical accretion are mineralogically similar to the shales of the drainage basin. However, most of the shales are calcareous whereas the vertical accretion contains only a trace of calcareous material.

Within the vertical accretion in the trench a thin, crude, discontinuous, very irregular layering caused by organic material occurs. Dark grey to black layers rich in organic material are $\frac{1}{4}$ to $1\frac{1}{2}$ in thick, highly irregular and contorted, and cannot be traced laterally for more than a few feet. The dark layers make up approximately one third of the 2-ft clay layer and contain from 2 to 4 times as much carbon as the enclosing lighter grey clays.

The illite peak on the diffraction trace was broader and more irregular for the samples of the dark layers than for other vertical accretion material.

All of the vertical accretion analyzed was oven-dried at 110°C, then heated to 850°C. The carbon constituted 0.8 to 3.2 percent of the dried samples and the ash constituted 88 to 92 percent.

Scattered irregularly throughout all the vertical accretion are lenses of peat from a few inches to a foot thick and up to 5 ft long. No large pieces of wood were found.

Other than the crude, discontinuous, dark-grey layering caused by organic content, no bedding was observed in the field nor was any seen under 40 power magnification in any of the samples taken from the trench or present floodplain. Although grain size distributions are irregular, there did not appear to be a silt-clay layering.

Twenty-eight hand-augered holes along and adjacent to the cross section penetrated 4 to 8 ft of alluvium. In all cases, the samples obtained were silty clay and peat except near bore hole 5 on the natural levee of Beaverdam Run, where thin layers of fine sand were encountered. The upper 8 ft, at least, of the entire floodplain west of the colluvial wedge is made almost entirely of vertical accretion which, in size distribution and clay mineralogy, is indistinguishable from the buried vertical accretion exposed in the trench. The material indicated as clay in the bore holes (fig. 3A) is also interpreted as vertical accretion.

SUMMARY OF FLOODPLAIN DEPOSITS

The cross section of Beaverdam Run at the Glendale Dam consists of colluvium, lag deposits, channel fill, lateral accretion, and vertical accretion. From the data available, it is difficult to estimate the proportions of these components in the area of the cross section bounded by the buried valley walls, the bedrock floor, and the present topographic surface.

Colluvium is an important contributor to the valley fill and comprises approximately one fifth of the total area of the cross section. Almost all the colluvium is in the eastern part of the floodplain, and it interfingers with alluvium on both sides. The colluvium exposed in the core trench has not been reworked by the stream, as indicated by the detrital coal and the orientation of the silt-

stone and sandstone slabs. On the western side adjacent to the line of cross section a tongue of colluvium appears to project below and east of the present position of Beaverdam Run.

Lateral Accretion

Lateral accretion forms a deposit up to 10 ft thick in the eastern half of the alluvial valley. In the core trench and bore holes 8 and 9 it forms a uniform bed containing local filled channels and lies on boulders, gravel, or bedrock. In the western part of the valley the lateral accretion is less thick and is usually found near the bottom of the valley fill. In bore hole 5 sand occurs interbedded with vertical accretion and, rather than representing lateral accretion, may represent the coarser fraction of overbank deposits laid down on the natural levee. It is also possible that some of the sand in bore hole 5 may represent splay deposits.

Vertical Accretion

Throughout the central and eastern part of the floodplain vertical accretion (clay) occurs high in the alluvial section overlying sand, gravel, or mixtures of these. In the core trench the clay rests in sharp contact on the lateral accretion. Discontinuous lenses of vertical accretion are found in the colluvium of the core trench (fig. 3B). Peaty material is found throughout the vertical accretion deposits.

In bore hole 5, clay occurs at the bottom of the valley fill and in bore hole 4 at the western edge comprises almost all of the alluvium and appears to interfinger with the colluvium.

Vertical accretion makes up almost the entire upper part (at least upper 8 ft) of the floodplain and overlies colluvium at the eastern and western sides. In the natural levee (bore hole 5) it is interbedded with sand.

Lag Deposits

Lag deposits of rounded boulders up to 1 ft in diameter are restricted to the lowest, eastern, part of the valley. They lie directly on the bedrock floor and are about 1 ft thick. No lag deposits occur high in the alluvial section.

Channel Fill

Small channel fill deposits of silt, sand, and gravel occur in the vertical and lateral accretion in the core trench. Gravel deposits contribute an important fraction of the alluvium in the central and west-central part of the floodplain (bore holes 5, 6, 7, 18, and 19). Because the cores from the bore holes are only a few inches in diameter, they give no accurate information on the real thickness of channel fill gravels which probably occur as irregularly distributed wedges. Nevertheless, the absence of gravel in the eastern part of the floodplain and its importance in the western and central parts is notable.

Splay Deposits

Splay deposits (Happ, Rittenhouse, and Dobson, 1940) associated with breeching of the natural levee cannot be specifically ascertained in the cross section. Some of the sand in bore holes 5 and 6 and very likely the sand near the bottom of bore hole 4 may be of this origin.

CONCLUSIONS

In the vicinity of the cross section, Beaverdam Run is an alluviating stream. At bankfull stage the stream is 4 to 4.5 ft deep; the bed of the stream is 20 to 25 ft above the bedrock floor. Thus, to reach bedrock the stream would have to scour to a depth about five times its water depth. Inglis (1949) noted that equilibrium channels may scour to a depth of only about 1.75 to 2 times the flow depth. Therefore it is probable that Beaverdam Run does not scour to bedrock under present conditions.

On the basis of the data given, the following recent history of Beaverdam Run is plausible. Beaverdam Run was a poised or slowly degrading stream, occupying a channel in the deep eastern side of the floodplain. At this time lag gravels were deposited in bore holes 9 and 10 (fig. 3A), lateral accretion in bore holes 7 and 8, vertical accretion in bore hole 5, and colluvium in bore hole 4. The stream then changed to an aggrading regime, perhaps because of deforestation of the area which occurred about 200 years ago. (Two hundred years is the tentative age of wood samples from the channel fill in the core trench.) As it aggraded, the

stream shifted westward across the floodplain with an irregular motion. Deposits in bore holes 6 to 9 are interbedded channel fill and lateral and vertical accretions. The extreme western edge (bore hole 4) received only vertical accretion. As the stream shifted westward and aggraded, colluvium built out from the east side and was not removed by the stream. Periodic floods caused deposition of the lenses of vertical accretion in small topographic lows in the colluvium (fig. 3B). The absence of coarse material in these lenses indicates that they were not deposited by a stream but from quiet water. During this time, the western side of the valley (bore hole 4) was filled with interbedded colluvium and vertical accretion. At present, the still aggrading stream has reached the western side of the valley.

ACKNOWLEDGMENTS

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FIGS. 1–13, JUNE, 1960

THE AMERICAN UPPER ORDOVICIAN STANDARD[1]

IV. CLASSIFICATION OF THE LIMESTONES OF THE TYPE CINCINNATIAN[2]

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ABSTRACT

The abundant ledges of limestone characteristic of the type Cincinnatian in the Ohio Valley can be grouped into several classes on the basis of a few criteria that are readily recognized in the hand specimen. Such a classification can make rock descriptions much simpler for those who measure sections there; furthermore, closer correspondence is now possible between the rock descriptions used or published by different workers. The petrographic properties of the seven classes are fully described and illustrated, although the limestone types are readily distinguished as follows:

1.—Fabric of whole and broken fossils randomly arranged; insoluble fraction small and localized.
2.—Fabric of broken and whole fossils oriented parallel to bedding; insoluble fraction moderate in amount and localized or disseminated
3.—Fabric of whole and broken fossils, either oriented or randomly arranged; insoluble fraction large.
4.—Fabric of finely broken fossil debris, insoluble fraction small and disseminated.
5.—Fabric of finely broken fossil debris, insoluble fraction moderate to large; rock laminated or cross-laminated.
6.—Fabric of very finely broken fossil debris; insoluble fraction large.
7.—Like number 6, but occurs as nodules.

INTRODUCTION

Purpose

One of the most trying aspects of geologic field work on the Upper Ordovician rocks of the Cincinnati region is the multiplicity of thin beds of shale and limestone and the apparent great variety of the kinds of limestone. Measuring a stratigraphic section is indeed tedious if each of the small units is described individually. Also, the rock descriptions gathered in this way do not reveal any unity or system that may occur among the limestones. Study has shown that the limestones may be grouped into the small number of classes that are described below. Knowledge of these classes will permit the field or laboratory geologist to measure or study stratigraphic sections with much more facility than formerly. Use of the classification permits ready determination of the relative abundances of the kinds of limestone in a section as well as interpretations of depositional environments that can be made from such data in conjunction with the characteristics of the several limestones. The accompanying classification is thus an analytic descriptive classification in the usage of Rodgers (1950).

Although the classification as it is here presented has already been used to advantage, others may find some modification helpful. It may well be that a similar classification would be effective for other rocks or regions that also display an abundance of small units of a limited variety of kinds of a major rock type.

Scope

The types of limestones recognized in this classification were first described from upper Cynthiana and lower and middle Eden beds exposed in the Ohio Valley above Cincinnati. Further work (Norman, 1959) demonstrated that these same seven classes occur also in the upper Eden beds. Reconnaissance by the authors showed that this same suite of seven limestone types includes the variety of limestones in the Maysville Group at Maysville,

[1] Other articles in this series have been published by the Journal of Paleontology (v. 33, no. 6, v. 34, no. 2), and the Ohio Division of Geological Survey (Info. Circ. no. 26).

[2] Manuscript received October 12, 1959.

Kentucky, and in the Maysville and Richmond Groups along Tanner's Creek in southeastern Indiana (Cumings and Galloway, 1913).

Names for the several kinds of limestone described herein have deliberately not been proposed. Suitable names, from standard general classifications of carbonate rocks, are listed under each class. These names are identical or closely similar for several of the limestone classes; the finer distinctions made in classifying the Cincinnatian limestones cannot be expressed by the standard general classifications. Nevertheless, names for our classes of limestone seem wholly unnecessary.

Methods

Hand specimens.—The hand specimen classification was established on the basis of more than 1400 samples of limestone from beds of the upper Cynthiana and lower and middle Eden that were collected by Edwards (1957) and Sharp (1957). Initially, approximately 200 specimens, representing a stratigraphic interval of more than 200 feet, were examined for their macroscopic characteristics. Thirty-two features such as grain size, sorting, color, orientation of fossils, and abundance of terrigenous material were placed as column headings on a chart. The specimen numbers of the 200 samples were listed on the left side of the chart and check marks were placed in the columns corresponding to those features found in each specimen. Careful study of the tabulated data revealed a consistent association of some ten of the 32 features, which permitted grouping of the specimens into six major types. The remaining 1200 specimens were then classified according to the types thus established. As this work proceeded, it became apparent that a variation of the types designated 1 and 2 increases in abundance in the middle and upper Eden and deserves recognition as a separate type. That new type was subsequently designated type 3. Reexamination of the lower Eden samples yielded only three specimens of type 3.

Norman (1959) then tested the classification while identifying some 400 additional samples from the upper Eden and basal Maysville beds and found the classification serviceable without further modification.

Thin sections.—The descriptions of the petrographic characteristics typical of each class of limestone are founded on a large sample of rocks. Thin sections of 85 samples of limestone were studied. These samples are from beds scattered throughout the upper Cynthiana and the entire Eden Formations. That fact made it possible to determine whether any certain limestone class might display different petrographic characters in different parts of the stratigraphic section, but no such systematic variations were found. The suite of thin sections also well represents the range of types of limestones. Certain classes are common and others are uncommon in occurrence, and the frequency of their occurrence is reflected in the number of sections studied from each class of rock.

Although the percentages of each of the minor constituents were estimated from each thin section and generalized from them into a percentage typical of each class of rock, these specifications are of uncertain advantage in certain of the classes. This is true because the minor constituents tend generally to be distributed irregularly, but not uniformly so, through the rocks. In the silty rocks the quartz grains are concentrated in the lower parts of the beds. Pyrite is usually more abundant in those rocks or parts of rocks that are abundant in fossils. The size and condition of fossils and fossil fragments often varies from bottom to top of a limestone bed. Such erratic qualities as these and others often make estimates of composition of the rock unrealistic for these constituents unless a larger sample of a bed than a thin section is available. Larger samples are used from which to obtain insoluble residues, and care is taken to assure that they represent the vertical span of the beds from which they come. For these reasons the amounts of accessory minerals typical of the several classes of limestone are derived partly from data concerning the insoluble residues of the samples from which the thin sections were prepared.

A minority of the limestone beds in any outcrop can be observed to grade from one limestone type to another, usually vertically. Sometimes the change is sharply marked; in such instances there are really two kinds of limestone cemented together rather than a progressive change from one

kind to another. Data recorded from such rocks have not been included in the generalization of the microscopic characters of the limestone classes, nor the macroscopic characters either, for that matter.

Insoluble residues.—Residues were prepared from a number of samples of each type of limestone by standard methods. The residues from baths in dilute hydrochloric acid were compared with those from acetic acid. Aside from the preservation of phosphatic brachiopods and conodonts in the acetic acid, such baths have no advantage and are slower. Upon removal of the acid the residues were dried and weighed. Then the fines were washed out by remoistening the samples and decanting; the remaining residues were dried and weighed, and are referred to as the washed residues. The depth of the suspension and the settling time preceding decantation were controlled in order that virtually all of the clay, most of the fine silt, and a bit of the coarse silt were removed.

Quantitative data from the insoluble residues of each type of limestone are expressed in the form of cumulative percentage curves, below, all for samples from the upper Eden Formation (Norman, 1959). Types 6 and 7 are relatively scarce in the Eden Formation. Consequently, so few samples of these types were collected that a statistical analysis of their insoluble residues is hardly valid. Nevertheless, since types 6 and 7 are petrographically equivalent except for structural differences, their residue data are combined and graphed.

The several hundred residues prepared by Edwards (1957) and Sharp (1957) could not be compared directly with the ones recorded here because they reported no total residues. Even so, their data concerning washed residues of each of the types of limestone were assembled and plotted. The resultant curves compare closely in form and position with the curves of the washed residues illustrated herein.

THE CLASSES OF LIMESTONES

The salient features of each class of limestone are described below. Colors are identified with reference to the Rock-Color Chart (Goddard, 1951). Grain sizes of the limestones are described according to the system of Cloud and Barnes (1948, p. 18).

Class 1

Hand-specimen characters.—The color of the fresh rock is medium dark gray to medium gray (N4 to N5). Some specimens have moderate yellowish-brown (10 YR 5/4) crystals on fresh surfaces, apparently not as a result of surface staining.

Randomly oriented whole to slightly broken fossils comprise about 50 percent of the rock (fig. 1). These float in a matrix of fossil fragments of sand size and smaller that are cemented by microgranular to medium-grained calcite. The sample illustrated in figure 1 is dominated by bryozoa, but similar fabrics may also be formed of whole brachiopods. The average size of the fossil fragments is slightly less than 1 cm, but occasional pieces may exceed 3 cm in length. With few exceptions, bivalve shells are disarticulated. The sorting of the biogenic debris is very poor.

Non-calcareous matter comprises, on the average, less than 5 percent of the rock. More than 90 percent of this material is silt and clay in lenses and pods or more rarely in discontinuous streaks or layers. The clay-silt ratio is rather uniformly about 3:1. Sand is very rare to absent.

Microscopic characters.—The random arrangement of fossil debris characteristic of hand specimens of type 1 is plainly evident in both thin sections and etched surfaces. Nevertheless, one usually can distinguish a lineation of the fine fossil debris that indicates bedding planes. The average size of fossil fragments in slides, about 3 mm, is considerably smaller than the apparent average size seen in hand specimens because of the difference in the scale of the field of view. There is a continuous gradation of debris size from fragments smaller than the limit of resolution under high magnification to fragments which are larger than the thin section. Loosely packed fossil debris ordinarily accounts for 25 to 40 percent of the rock. The sorting is invariably poor.

The matrix is composed of a mosaic of clean very fine- to medium-grained anhedral calcite. The mosaic may be locally argillaceous, and the sparry calcite grains may reach 2 mm in diameter. Characteristically, those areas of the thin section containing the smallest grains of calcite are the ones with the small clay fraction that clouds the cal-

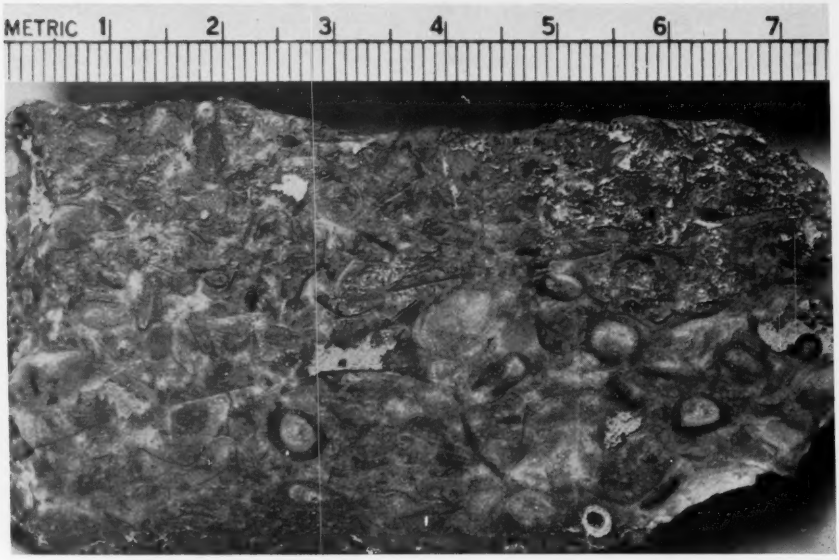

FIG.1.—Polished and etched surface of a sample typical of Class 1 limestones. Sample is sectioned normal to bedding and oriented as in the field. From middle of the McMicken "Member" at Rising Sun, Indiana. Scale numbered in centimeters.

cite. Some dolomite occurs in small particles adjacent to shell fragments and peripheral to coarsely crystallized patches of the matrix. Dolomitic matrices are common only in Class 1 limestones, and the dolomite does not exceed 2 percent of the rock. Dolomite is most easily identified by stain tests on ground and etched surfaces.

Only three accessory minerals occur in sufficient abundance to deserve attention: clay, pyrite, and collophane. Clay is found disseminated throughout the matrix and occurs in pods in the more argillaceous examples of this type of limestone. Some of the larger clots of clay are stained a yellow or brown color, probably by limonite. Pyrite occurs as a partial replacement of brachiopod shells and trilobite carapaces and as scattered microgranular octahedra in the matrix. Pyrite in all forms makes up between 1 and 2 percent of the rock. Collophane occurs in most thin sections of limestones of this class in amounts not exceeding 1 percent of the rock. The collophane occurs most commonly as kidney-shaped sand- and silt-size pellets.

Insoluble residue.—Figure 2 displays curves showing both the range of amounts of insoluble residues for a number of samples and the degree of uniformity of size of residue for those samples. The residues consist of clay, silt, and pyrite for the most part in a ratio of approximately 6:2:1. Commonly, a few grains of cellular brownspar occur in samples which contain an abundance of bryozoan remains.

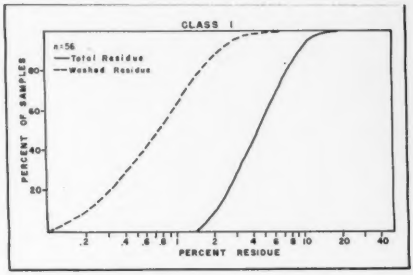

FIG. 2.—Cumulative curves of insoluble residues of limestones of Class 1.

Applicable names.—(1) Biocalcilyte and hydrocalcirudyte of Grabau (1924). (2) Autochthonous and coquinoid limestones of Pettijohn (1957). (3) Calcarenitic limestone and coarse carbonate clastic and their partially recrystallized equivalents of Bramkamp and Powers (1958). (4) Biosparrudite (Ib:Lr) and biomicrudite (IIb:Lr) of Folk (1959).

CLASS 2

Hand-specimen characters.—The color of the fresh rock is medium dark gray to medium gray (N4 to N5). An occasional specimen may be moderate yellowish brown (10 YR 5/4).

Whole to slightly broken fossils float in a matrix of small fossil fragments cemented by microgranular to fine-grained calcite. Coarse fossil debris makes up approximately 30 percent of the rock. These fragments are systematically arranged so that the rock has a distinct lineation parallel to bedding surfaces (fig. 3). Their average size is less than 1 cm in longest dimension, but occasional fragments may exceed 2 cm. Bivalve shells are disarticulated and lie with convex surfaces uppermost. The biogenic debris (allochems of Folk, 1959, p. 4) is generally poorly sorted.

Typical samples contain between 5 and 6 percent of non-calcareous constituents, of which over 90 percent is silt and clay that occur in thin streaks and layers or less commonly in pods and lenses. The clay-silt ratio is approximately 3:1. Sand ordinarily is absent.

Microscopic characters.—Thin sections of limestones of Class 2 show the systematic arrangement of the large planar fossil fragments typical of the hand specimens. Nevertheless, fragments smaller than 0.3 mm, considered a part of the matrix, are frequently in such a state of disorder that without the presence of the larger fragments it would be difficult to determine vertical and horizontal fabric axes in the rock. The average length of fossil fragments is approximately 1.5 mm, approximately half as large as the average fragment in rocks of Class 1. Approximately 35 to 50 percent of the rock consists of fairly tightly packed, poorly sorted fossil debris; this debris is generally

FIG. 3.—Polished and etched surface of a sample typical of Class 2 limestones. Sample is sectioned normal to bedding and oriented as in the field. From upper part of the McMicken "Member" on Ninemile Creek, Clermont County, Ohio. Scale numbered in centimeters.

somewhat better sorted than in type 1 rocks.

The matrix of these rocks is predominantly argillaceous microgranular calcite, but patches of mosaic of clear anhedral calcite crystals, 0.05 mm to 0.5 mm in diameter, occur. Those specimens containing the most clay have, without exception, the finest-grained matrix. Pellets of dirty, clayey aggregates of very finely crystalline calcite occur frequently within the anhedral calcite mosaic of specimens of this class. They are ovoid, 0.2 mm to 0.25 mm in diameter, poorly translucent because of the contained clay, and may well be fecal pellets. Such pellets are more common in those samples having the larger insoluble residues.

Clay is disseminated throughout the matrix, concentrated in thin streaks, and gathered in the pellets. Pyrite comprises less than 1 percent of the rock; as in Class 1, it replaces fossil structures and occurs as aggregates of grains scattered through the matrix. Collophane pellets were identified in most thin sections but never in amounts exceeding 2 percent of the rock. A few grains of quartz silt occur in most thin sections.

Insoluble residue.—Figure 4 displays curves showing both the range of amounts of insoluble residues for a number of samples and the degree of uniformity of size of residue for those samples. The residues consist of clay, silt and pyrite. Those examples of this class which contain abundant bryozoan remains contain a few grains of cellular brownspar.

Applicable names.—(1) Biocalcilyte and hydrocalcirudyte of Grabau (1924). (2) Allochthonus limestones and coquinas of Pettijohn (1957). (3) Calcarenitic limestone and coarse carbonate clastic, and their partially recrystallized equivalents, of Bramkamp and Powers (1958). (4) Biosparrudite (Ib:Lr) and biomicrudite (IIb:Lr) of Folk (1959).

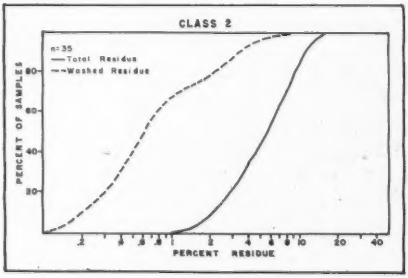

FIG. 4.—Cumulative curves of insoluble residues of limestones of Class 2.

CLASS 3

Hand-specimen characters.—The color of the fresh rock is dark gray to yellowish-brown (N3 to 10 YR 4/2).

Whole to slightly broken fossils float in a matrix of silt, clay, and microgranular to very fine-grained calcite cement (fig. 5). The larger pieces are mostly whole valves; fine chips of fossil debris are less abundant than in Classes 1 and 2. Clay laminae often bend around fossils, apparently as a result of differential compaction. The fossils in rocks of this class have a random or, more commonly, a linear arrangement. Their average length is less than 1 cm, but occasional individuals may exceed 3 cm. Articulated bivalve shells are common. The fossil debris is moderately well sorted.

The typical specimen of Class 3 contains about 10 to 25 percent of non-calcareous matter, mostly silt and clay. The clay-silt ratio is highly variable, but averages about 2:1. Sand is virtually absent. The rock has a tendency to split along clay laminae in samples having distinct lineation.

Microscopic characters.—Large fossil fragments in the limestones of Class 3 are randomly arranged in some specimens and systematically aligned parallel to bedding planes in others. They constitute a greater proportion of the allochems in this limestone type than in any of the others. The allochems, however, normally account for less than 30 percent of the rock, considerably less than in any of the other classes. Most of the fossil debris viewed in thin section is 0.5 cm or more in length and is moderately well sorted. The clayey or silty streaks and layers seen readily in hand specimen were not observed in thin section, probably because such layers bounded, rather than crossed, the durable samples taken for later thin-sectioning. Nevertheless, the more terrigenous nature of rocks of Class 3 is clearly evident from those parts of the rock that do not include such silty or clayey streaks. Dahl-

FIG. 5.—Polished and etched surface of a sample typical of Class 3 limestones. Sample is sectioned normal to the bedding and oriented as in the field. From middle of the McMicken "Member" in Happy Hollow Creek, Clermont County, Ohio. Scale numbered in centimeters.

lite, probably fragments of conodonts, was observed in one slide.

The matrices of all the samples of Class 3 consist of at least 75 percent of dirty, microgranular calcite. Calcite crystals rarely exceed 0.1 mm in length, except where small cavities have been filled with clear calcite. There the mosaics may contain crystals up to 0.5 mm or larger. These cavities are not, however, found in every specimen, and where present, are usually smaller than 2 sq mm in area.

Insoluble residue.—Quantitative data concerning the residues are shown in figure 6. Clay and quartz silt are essential minerals in rocks of Class 3, although the latter may constitute as little as 2 or 3 percent of the rock. The clayey streaks so common in hand specimens are recognized in thin section only when the slide is viewed without magnification. Most of the clay is scattered throughout the matrix, as are the silt grains. Pyrite and collophane occur in approximately the same amounts and in the same manner as in Classes 1 and 2. A few grains of cellular brownspar often occur in those samples that contain abundant bryozoa.

Applicable names.—(1) Biocalcilyte and hydrocalcirudyte of Grabau (1924). (2) Autochthonous and coquinoid limestones of Pettijohn (1957). (3) Calcarenitic limestone and partially recrystallized equivalents of Bramkamp and Powers (1958). (4) Silty, clayey biosparrudite (Tzc Ib:Lr) of Folk (1959).

CLASS 4

Hand-specimen characters.—The color of the fresh rock is dark gray to dark yellowish-brown (N3 to 10 YR 4.2). An example of the class is shown in figure 7.

Finely broken fossil fragments are cemented by microgranular to very fine-grained calcite. Most of the calcareous debris falls in the coarse to very coarse sand size range (0.5 to 2.0 mm), but an occasional fragment may reach 5.0 mm in length. The allochems (Folk, 1959, p. 4) are well sorted and commonly lie parallel to bedding planes. They consist mostly of fossil debris and some reworked sediment (intraclasts) and comprise 70 percent or more of the rock.

Non-calcareous materials account for less than 5 percent of the typical specimen of Class 4. Clay and silt occur in approximately

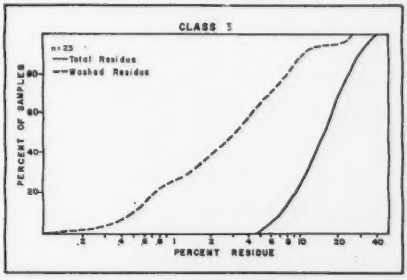

FIG. 6.—Cumulative curves of insoluble residues of limestones of Class 3.

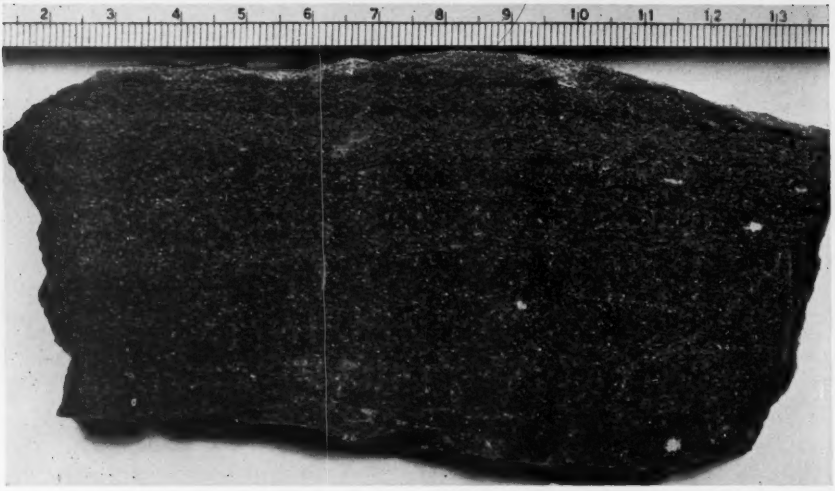

FIG. 7.—Polished and etched surface of a sample typical of Class 4 limestones. Sample is sectioned normal to bedding and oriented as in the field. From upper Southgate "Member" in Ferguson Run, Clermont County, Ohio. Scale numbered in centimeters.

equal proportions, usually disseminated, but occasionally in small pods and lenses. Siliceous sand grains are exceedingly rare.

Microscopic characters.—Limestones of this class are easily recognized as a distinct type in thin section. Fossil debris and some intraclasts (Folk, 1959, p. 4) make up at least 70 percent of the rock, but, contrary to their mode of occurrence in Classes 1, 2, and 3, they are always well sorted. Fragments of fossils range in size from 0.2 mm to 1.0 mm and average about 0.5 mm. Planar elements are well oriented parallel to bedding surfaces.

At least half of the matrix of these limestones is composed of clear, anhedral, sparry, calcite crystals which range from 0.05 mm to 0.75 mm in size. Some of the larger crystals completely enclose small fossil fragments. The microcrystalline portion of the matrix is scattered throughout the rock in small argillacaeous patches or bands.

There appears to be no difference between the quality, quantity, or mode of occurrence of the accessory minerals in this class and those found in limestones of Class 1.

Insoluble residue.—Figure 8 shows curves indicating both the range of amounts of insoluble residues for a number of samples and the degree of uniformity of size of residue for those samples.

Applicable names.—(1) Biocalcilyte or hydrocalcarenyte of Grabau (1924). (2) Calcarenite, encrinite, or microcoquina of Pettijohn (1957). (3) Calcarenite and calcarenitic limestone, and their partially recrystallized equivalents, of Bramkamp and Powers (1958). (4) Intrasparite (Ii:La), biosparite (Ib:La), and biopelsparite (Ibp:La) of Folk (1959).

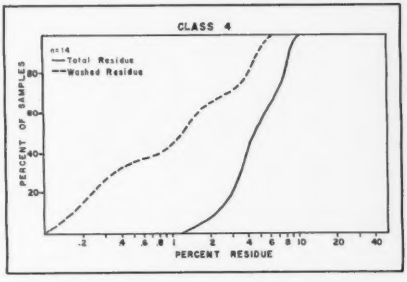

FIG. 8.—Cumulative curves of insoluble residues of limestones of Class 4.

CLASS 5

Hand-specimen characters.—The fresh color of most specimens is medium dark gray (N4), and a few are dark greenish-gray (5 GY 4/1).

Very finely broken fossil debris, pellets, and intraclasts are cemented in microgranular to very fine-grained calcite. The calcareous debris runs the gamut of sand-size particles. Non-calcareous particles in the silt to fine-grained sand range occur in thin streaks or layers and impart a distinct lineation to the rock (fig. 9). Sand-size allochems lie parallel to bedding surfaces. The silty fraction is commonly cross-stratified.

The average specimen contains about 10 percent of impurities, of which at least half is of silt size and larger. Particles of clay size are disseminated throughout the rock, but silt and sand grains are largely concentrated in discrete laminae. Sand grains are unimportant.

Microscopic characters.—Limestones of this type consist mostly of small fragments of fossils, clay, pellets of dirty, clayey calcite (intraclasts), and an enclosing mosaic of anhedral calcite. The fragments of fossils are typically less than a millimeter in length, and they make up about one-fifth of the rock. Small patches of clay, probably spheroidal or ovoid in the solid, and a millimeter or so in diameter, are scattered abundantly through the thin section. Similar pellets or aggregates of dirty calcite also occur and are considered to be similar features having less clay within them. Quartz-mica silt may occur and is always concentrated near the base of the bed. The entire rock is distinctly and finely laminated parallel to or oblique to the bedding surfaces. This characteristic is also clearly evident in the hand specimen, especially if it is somewhat weathered.

The anhedral calcite of the cementing mosaic consists of grains smaller than 0.02 mm for the most part. Because of the clay content of such crystals their boundaries can be recognized only under crossed nicols. Individual crystals often completely enclose tiny fossil fragments.

The dirty character of the limestones of Class 5 makes it difficult to estimate the percentages of the constituent minerals from the thin section and insoluble residues must be obtained for determination of relative quantities of calcite and the several insolubles. Muscovite and chlorite together make up less than 1 percent of the samples having abundant silt. Pyrite occurs in amounts ranging from 2 to 5 percent of the rock and occurs as scattered aggregates of tiny crystals as well as replacements of some

FIG. 9.—Polished and etched surface of a sample typical of Class 5 limestones. Sample is sectioned normal to bedding and oriented as in the field. From middle of the McMicken "Member" on Ninemile Creek, Clermont County, Ohio. Scale numbered in centimeters.

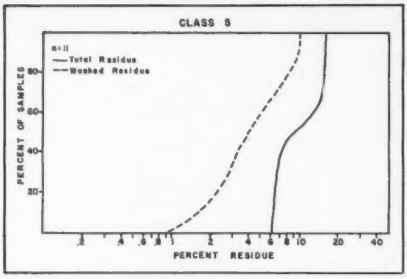

FIG. 10.—Cumulative curves of insoluble residues of limestones of Class 5.

of the particles of fossil debris. Limonite, probably derived from the pyrite, may make up as much as 1 percent of the rock. Collophane is uncommon and is less than 1 percent of the rock when it does occur.

Insoluble residue.—Figure 10 displays curves indicating both the range of amounts of insoluble residues for a number of samples as well as the degree of uniformity of grain size of residues for those samples. The composition of the residues is obvious from the discussion above.

Applicable names.—(1) Siliceous hydrocalcarenyte of Grabau (1924). (2) Silty calcarenite and silty microcoquina of Pettijohn (1957). (3) Impure calcarenitic limestone and impure partially recrystallized calcarenitic limestone of Bramkamp and Powers (1958). (4) Silty intrasparite (Tz Ii:La), silty biosparite (Tz Ib:La), and silty biopelsparite (Tz Ibp:La) of Folk (1959).

CLASS 6

Hand-specimen characters.—Rocks of this class are typically very uniform in color—a medium greenish-gray (5 GY 5/1).

Class 6 limestones are composed of finely broken fossil debris cemented in a highly argillaceous microgranular to very fine-grained calcite matrix. Fully 90 percent of the fragments are of silt size. Siliceous silt grains normally are evenly disseminated throughout the rock but occasionally may be concentrated in cross-stratified laminae. The texture is remarkably uniform in all specimens and in all parts of each specimen (fig. 11).

Silt and clay together constitute 25 to 50 percent of the limestones of this type. The clay-silt ratio usually exceeds 2:1. Highly argillaceous specimens may show a tendency to cleave along clayey streaks.

Microscopic characters.—Fossil fragments and shards can be identified, but they are always less than 0.1 mm in greatest dimension. The larger of such fragments are sometimes aligned crudely parallel to bedding planes.

The silt consists principally of quartz and subordinately of feldspar in medium to coarse grains. The lamination sometimes observed in hand specimen is not discernible in thin section with magnification.

The fossil fragments and silt fractions are cemented by a matrix of very dirty anhedral calcite mosaic. In some samples the crystals of the mosaic equal or exceed 0.004 mm in diameter, the upper limit of microcrystallinity according to Folk (1959, p. 8). In other samples the mosaic is predominantly microcrystalline calcite.

Mica, chlorite, hematite, limonite, pyrite, collophane, and tourmaline all were identified in the coarse silt fractions of samples of this class. The pyrite occurs as scattered grains and aggregates to a limit of 3 percent in the coarser grained examples of the class. The others of these accessories, taken together, make up less than 1 percent of these rocks.

Insoluble residue.—The accessory minerals are more easily studied in mounts of insoluble residues than in thin section. Figure 12 presents the quantitative aspects of the residues from rocks of Class 6.

Applicable names.—(1) Siliceous and argillaceous hydrocalcilutytes of Grabau (1924). (2) Argillaceous calcisiltite or argillaceous calcilutite of Pettijohn (1957). (3) Impure fine-grained limestone of Bramkamp and Powers (1958). (4) Clayey micrite (Tc IIIm:L) of Folk (1959).

CLASS 7

Hand-specimen characters.—Most specimens are medium gray to medium light gray (N5 to N6); some are medium greenish-gray to greenish-gray (5 GY 5/1 to 5 GY 6/1).

Rocks of this class are impure nodular limestones (fig. 13). Individual nodules have a core consisting of fine silt grains cemented by argillaceous microgranular calcite. The silt grains are often concentrated in streaks

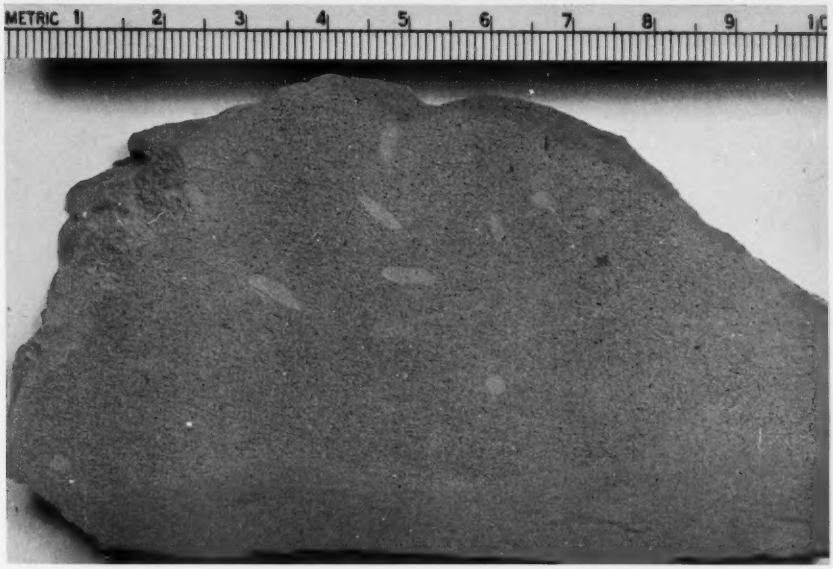

FIG. 11.—Polished and etched surface of a sample typical of Class 6 limestones. Sample is sectioned normal to bedding and oriented as in the field. From the middle of the Southgate "Member" on Ferguson Run, Clermont County, Ohio. Scale numbered in centimeters.

and very thin layers which may be gently arched or cross-stratified. The periphery of a nodule is highly argillaceous.

The average Class 7 rock contains the same impurities in about the same proportion as those of Class 6.

Microscopic characters.—The fossil fragments and the terrigenous fractions are substantially as they are in rocks of Class 6, except that the fossil fragments are somewhat finer. The cementing mosaic of dirty calcite is like that of Class 6; the same is also true of the accessory minerals.

Insoluble residue.—Class 7 is distinguished from Class 6 on the basis of structure; their compositions are substantially the same. Insoluble residues of rocks of Class 7 are recorded with those of Class 6 in figure 12.

Applicable names.—The names applicable to rocks of Class 6 also serve for those of Class 7.

Summary Diagnosis of the Classes

Through the preceding detailed descriptions of the characteristics of each of the seven classes of limestone the reader may have lost sight of the fact that the classes are readily distinguishable on the basis of only a few expressions of fabric, texture, and composition. For convenient review and reference these criteria are arranged in table 1.

Comparisons among the Classes

The distinctions between certain pairs of

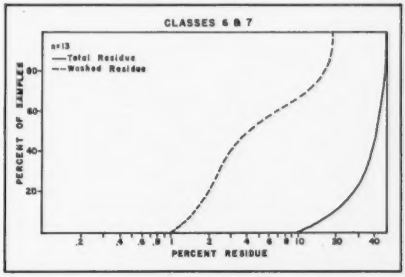

FIG. 12.—Cumulative curves of insoluble residues of limestones of Classes 6 and 7.

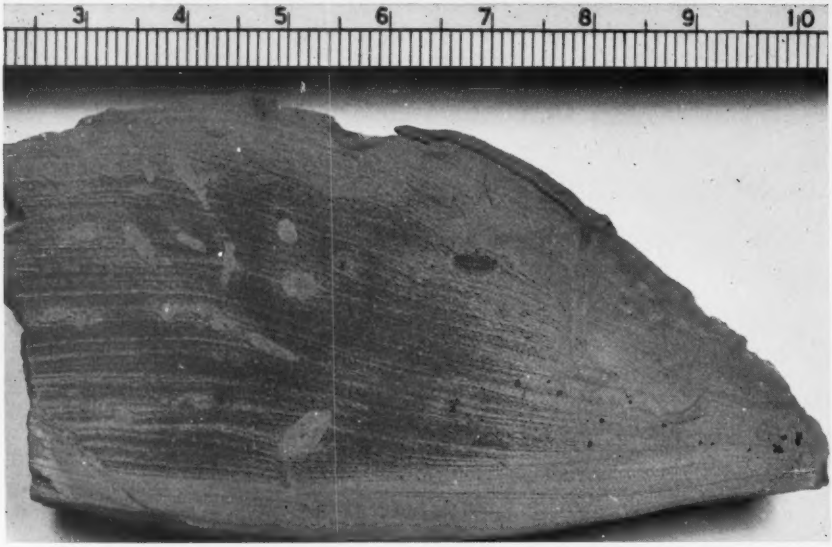

FIG. 13.—Polished and etched surface of a sample typical of Class 7 limestones. Sample is sectioned normal to bedding and oriented as in the field. From middle of the McMicken "Member" on Happy Hollow Creek, Clermont County, Ohio.

limestone classes are to some degree artificial because of a continuous gradation of some of the qualities used to define the classes. As a consequence of this fact rocks occur that are intermediate between typical examples of certain classes. With seven different classes of limestone as end-members, 21 pairs of classes are possible between which intermediates might be expected. Happily, intermediates are common only between a few of the possible end-member combinations: classes 1 and 2, 1 and 3, 2 and 3, and 5 and 6. Intermediates between the following possible end-member combinations are found only occasionally: classes 1 and 4, 2 and 4, and 4 and 5.

Intermediates of three qualities occur between classes 1 and 2. A small minority of samples that are clearly of Class 1 in the hand specimen show a definite alignment of microscopic fossil debris parallel to the bedding. A number of thin sections of rocks of Class 2 show randomly oriented microscopic fossil debris. Hand samples occur in which some valves and fossil fragments are aligned parallel to bedding and others are jumbled about. Only the third condition is of concern in using the classification; an intermediate rock sample falls into either class according to whether the oriented or jumbled macroscopic fragments predominate.

As rocks having a fabric typical of either Class 1 or Class 2 contain more and more insoluble material they grade to Class 3. At least 90 percent of the examples of Classes 1 and 2 have insoluble fractions of less than 10 percent, whereas more than 80 percent of examples of Class 3 have insoluble fractions in excess of 10 percent. Furthermore, more than 20 percent of the samples of type 3 have residues in excess of 25 percent of the rock. The small clay-silt fractions of type 1 rocks and type 2 rocks occur characteristically in small pods or lenses; in type 3 rocks the larger clay-silt fraction pervades the rock more uniformly. This difference in mode of occurrence of the clay-silt fraction is sufficient to differentiate most of these intermediate examples.

All rocks of Class 5 have less than 20 percent of insoluble residue, whereas 90 percent of those of type 6 have more than 20 percent

TABLE 1.—*Principal distinguishing characteristics of the classes*

Class	
1	Whole and broken fossils randomly arranged; insoluble fraction small and localized
2	Broken and whole fossils oriented parallel to bedding; insoluble fraction moderate in amount and localized or disseminated
3	Whole and broken fossils, either oriented or randomly arranged; insoluble fraction large
4	Finely broken fossil debris; insoluble fraction small and disseminated
5	Finely broken fossil debris; insoluble fraction moderate to large; rock laminated or cross-laminated
6	Very finely broken fossil debris; insoluble fraction large
7	Very finely broken fossil debris; insoluble fraction large; occurs as nodules

of insoluble residue, some having as much as 50 percent of insoluble material. The curves of washed and total insoluble residues (figs. 10 and 12) show that the clay-silt ratio is far larger in type 6 rocks than in type 5 rocks. Samples that are intermediate between classes 5 and 6 can often be classified without recourse to study of their insoluble fractions by calling those samples that are laminated or cross-laminated type 5. This simplification is justified by the observed fact that laminae are well-developed in those rocks with a high silt-clay ratio.

Classes 1 and 2 grade to Class 4 as the fossil debris decreases in size and the sorting improves. It is indeed fortunate that few rocks seem to be truly intermediate in these respects; the limestones seem either to have large and numerous fossils and fragments or to have fragments of a rather uniform small size that makes their recognition difficult in the hand specimen.

The silty laminae typical of Class 5 rocks are not always apparent on fresh surfaces. Samples that cannot be classified with confidence in the field as a 4 or a 5 may be quickly resolved by observation of an etched surface in the laboratory. Thin sections reveal such laminae only if viewed without magnification.

RELATIVE ABUNDANCE AND DISTRIBUTION OF LIMESTONE CLASSES

Table 2 shows the relative abundance of the several limestone types in the Cynthiana and Eden Formations. Data for the upper Cynthiana and lower Eden beds, collected by Edwards (1957), and for the middle Eden beds, collected by Sharp (1957), were compiled from hand samples classified in the laboratory by Norman. Only examples of Class 3 can be said to show a trend of occurrence.

In all the measured sections every limestone bed thicker than one inch was sampled, and the percentages in table 2 are based on a count of the beds of each limestone type. For all the limestones except types 6 and 7 the range and frequency of bed thicknesses are about the same. Thus the percentages provide a rough estimate of the relative volumes of the various limestone types. Classes 6 and 7 represent a somewhat smaller portion of the total volume of lime-

TABLE 2.—*Relative abundance of limestone classes in the Cynthiana and Eden Formations*

Number of Sections Measured	Stratigraphic Unit	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7
8	Upper Eden	39.3%	22.4%	15.6%	9.0%	5.1%	7.6%	1.0%
8	Middle Eden	32.8	31.6	5.5	4.4	16.3	6.3	3.1
10	Lower Eden	38.9	23.4	0.6	2.8	27.7	3.5	3.1
9	Upper Cynthiana	43.7	20.8	0.4	10.0	19.1	1.7	4.3
	Unweighted Averages	38.6	24.5	5.5	8.5	17.1	4.7	2.8

stone than the figures indicate because they seem never to occur in beds exceeding 3 or 4 inches in thickness, whereas a considerable portion of the other types occur in beds twice this thickness.

Vertical distributions of the limestone types seem to follow no definite pattern. Occasionally three or four limestone beds, intercalated with shale, will be of a single class, but more often adjacent beds are of different classes of limestone. It appears that any one type can occur sandwiched between beds of any other class or classes.

Laterally, a similar relation prevails. Some beds or groups of beds of rock of a given class appear to persist over a distance of five to ten miles, but others that can be correlated from one section to another, on the basis of lithologic sequence, are not everywhere of the same type of limestone.

ACKNOWLEDGMENTS

The work with hand specimens was supported by Development Fund Project 5813 of The Ohio State University. Petrographic thin sections used for this study were purchased by the Graduate School of the University. The writers appreciate these important means of assistance that made their work possible.

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PLATE 1, FIGS. 1–2, JUNE, 1960

THE EFFECT OF STRONTIUM ON THE ARAGONITE-CALCITE RATIOS OF PLEISTOCENE CORALS[1]

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ABSTRACT

The Pleistocene coral reefs which form the upper Florida Keys are in a state of alteration from aragonite to calcite. A quantitative relationship between the strontium content of the corals and their aragonite-calcite ratios was found. Strontium and calcium determination were made with a Zeiss flame photometer. Aragonite-calcite ratios were determined qualitatively with Meigen stains and quantitatively using X-ray techniques. Where the stains showed that aragonite was high relative to calcite, the strontium content was correspondingly high. Where the stains indicated that calcite was dominant, the strontium content was low. X-ray analyses confirmed these results. In several cases it was noted that within a single sample there were distinct areas which were aragonite and others which were calcite. These sections were separated and analyzed. In all such cases the aragonite portion of a sample contained about twice as much strontium as did the calcite portion of the same sample. It is suggested that strontium content is a factor which inhibits the alteration of aragonite to calcite under natural geologic conditions, and only when much of the strontium is removed may the alteration take place.

INTRODUCTION

Previous Work

The mechanics of the alteration of aragonite to calcite have long intrigued the geoscientist. Some of the factors involved in the kinetics and the thermodynamics of the inversion have been determined. Kobayashi (1951 a, b), Jamieson (1953), MacDonald (1956), and others have demonstrated that temperatures and pressures much greater than those existing at the surface of the earth can bring about the crystallographic inversion to the stable form, calcite. It has been firmly established that the alteration proceeds at a slow rate at standard temperature and pressure (Lowenstam, 1954).

Odum commented upon the analyses of some Bikini limestones (Emery, Tracey, and Ladd, 1954) and suggested the use of strontium content as an index of recrystallization or replacement of limestones.

The role played by strontium in the laboratory precipitation of calcium carbonate was emphasized by the experiments of Zeller and Wray (1956) and Wray and Daniels (1957). They clearly demonstrated that the presence of strontium in a solution from which calcium carbonate was to be precipitated forced that carbonate to crystallize in the orthorhombic form, aragonite, even under conditions of temperature and pH which would normally have produced the hexagonal form, calcite.

These data indicated to the author that the type of index suggested by Odum might reveal some interesting information on the alteration process of aragonite to calcite.

Calculations

In the following text and in tables 1 and 2 the calcium and strontium contents of the Pleistocene coral specimens are reported as percent of constituents in the oven-dried samples. The strontium to calcium atom ratios are reported in the terms most familiar to geologists and geochemists. For example, a sample of *Montastrea* sp. No. 7, from 1.4 miles southwest of Treasure Harbor contains 0.545 percent strontium and 39.67 percent calcium. The Sr/Ca atom ratio $\times 1000$ would then be:

$$\frac{0.545/87.63}{39.67/40.08} \times 1000 = 6.29$$

This indicates that there are present approximately 6 atoms of strontium for every 1000 atoms of calcium. By presenting the information of strontium in this way it is possible to compare the strontium content with the more familiar calcium content.

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TABLE 1.—*Strontium and calcium analyses and aragonite-calcite contents of Pleistocene corals from the Florida Keys*

Specimen	Location	Ca percent	Sr percent	Sr/Ca ratio	Aragonite percent	Calcite percent
Montastrea sp. No. 7	1.4 miles SW of Treasure Harbor	39.67	0.545	6.29	5	95
Diploria sp. No. 1		39.19	0.816	9.52	50	50
Diploria sp. No. 8		38.81	1.030	12.14	100	0
Diploria sp. No. 10		39.17	0.499	5.83	25	75
Porites sp. No. 17		38.60	1.070	12.68	100	0
Montastrea sp. No. 9	0.6 miles SW of Treasure Harbor	39.63	0.915	10.56	60	40
Diploria sp. No. 12		39.09	1.003	11.73	90	10
Diploria sp. No. 15		39.25	0.954	11.12	80	20
Diploria sp. No. 18		39.50	0.940	10.88	75	25
Montastrea sp. No. 5	Cutoff for White Marlin Beach	38.64	1.046	12.38	95	5
Diploria sp. No. 13		38.64	0.719	8.51	40	60
Montastrea sp. No. 11	Pigeon Key	39.89	1.042	11.95	93	7
Diploria sp. No. 3		38.70	0.862	10.19	70	30
Montastrea sp. No. 16	1.3 miles SW of Jewfish Creek	39.61	1.012	11.69	90	10
Diploria sp. No. 14		38.96	0.959	10.10	50	50
Diploria sp. No. 4	3.3 miles NE of Tavenier Creek Bridge	39.21	0.536	6.25	5	95

The Problem

Along the Florida Keys, original aragonite is found in association with material partially or completely altered to calcite. This study was concerned with a factor which might have influenced the alteration process and the degree to which the alteration proceeded.

SAMPLING LOCALITIES

The area of the Florida Keys was selected for this study because the Pleistocene coral reef material of that area, originally 100 percent aragonite, has not been subjected to temperatures and/or pressures very different from those existing today. Yet, as previously noted, the aragonite was found in direct association with material partially or completely altered to calcite.

The Pleistocene coral material was sampled at six localities along the Florida Keys (fig. 1). The author believes that the samples were representative of the areas from which they were collected since they were in place and not visibly weathered. Locations were determined from the U. S. Coast and Geodetic Survey Chart 1249.

CHEMICAL ANALYSES

The presence and concentration of the strontium and calcium ions were determined by flame photometric analysis using the Zeiss Spectrophotometer PMQ II with flame equipment.

Standard Solutions

All the chemicals used in this investigation were of analytical grade and were tested for traces of the cations being investigated. A stock solution of calcium, 250 parts per million (ppm), was prepared by dissolving 1250.87 mg of calcium carbonate in 10 ml of 6N hydrochloric acid (HCl) and diluting to two liters; a stock solution of strontium, 200 ppm, was prepared by dissolving 966.10 mg of strontium nitrate in 10 ml of 6N hydrochloric acid and diluting to two liters.

From these stock solutions, suitable aliquots were taken and diluted for comparison standards from which calibration curves

were made. Calibration curves were obtained by plotting the concentration of the ion against its percent emission.

Preparation of Samples for Analysis

The samples were cleaned, air-dried, and crushed manually using an agate mortar and pestle. They were placed in porcelain crucibles and heated in an oven at a temperature of 350°C for 8 to 12 hours and then cooled. At this temperature the organic matter was presumed to have been completely oxidized. The ash residues were placed in sterilized vials and these were stored in a desiccator.

Duplicate weighed samples, 0.5 and 1.0 gm of the ash residues, were treated with 10 and 20 ml of distilled water and 2.5 and 5.0 ml of 6N HCl respectively. The unknown solutions were filtered into 500 ml and 1000 ml volumetric flasks and diluted to the required volumes. In no case was the weight of the filtered residue greater than 5 mg, and in most cases it was much less, thus being relatively insignificant. The solutions were thoroughly mixed and analyzed for strontium and calcium using the standard addition and dilution technique of flame photometry after Dippel (1954). The error involved in this type of analysis is of the order of ± 10 percent.

ARAGONITE-CALCITE ANALYSIS

Qualitative

Meigen's (1901) cobaltous nitrate stain was used in addition to a silver nitrate-manganous nitrate stain and a silver sulfate-manganous sulfate stain. The three stains darken aragonite but leave calcite uncolored or very slightly colored. They were used on consecutively cut sections of the coralline material $\frac{1}{16}$- to $\frac{1}{8}$-in thick, and the results of each were complimented by the other two stains. This was to be expected since the staining action of each method is based on the differential solubilities of aragonite and calcite.

Cobaltous nitrate stain.—A section of Pleistocene coral was placed in a porcelain casserole and immersed in a 0.3M solution of cobaltous nitrate. The aragonite turned a lilac color after the section had been boiled for 10 to 20 minutes, and the calcite remained either uncolored or was tinged a light blue.

Silver nitrate-manganous nitrate stain.—Five to 10 gm of silver nitrate were added to 100 ml of a 50 percent solution of manganous nitrate; the resulting solution was diluted to twice its volume. The solution was placed in a porcelain casserole and a section of coral was heated in it until the solution reached the boiling point. The aragonite turned black and the calcite remained uncolored or turned a very light gray.

Silver sulfate-manganous sulfate.—This stain works in the same way as did the silver nitrate-manganous nitrate stain. The proportions of reagents were the same except for the silver sulfate. Only $\frac{3}{4}$ gm of silver sulfate were dissolved in 100 ml of a 50 percent manganous sulfate solution.

Quantitative

Measurement of relative intensities of X-ray reflections characteristic of each mineral

TABLE 2.—*Strontium and calcium analyses and Sr/Ca ratios of adjacent sections of aragonite and calcite of Pleistocene corals*

Specimen	Location	Ca percent	Sr percent	Sr/Ca ratio
Montastrea sp. No. 6	1.4 miles SW of Treasure Harbor			
Aragonite		37.22	1.004	12.34
Calcite		39.67	0.480	5.53
Montastrea sp. No. 7				
Aragonite		37.87	1.150	13.89
Calcite		39.65	0.595	6.79
Montastrea sp. No. 9	0.6 miles SW of Treasure Harbor			
Aragonite		38.39	1.048	12.49
Calcite		38.72	0.547	6.46

provided the basis for quantitative determinations of aragonite-calcite contents. Lowenstam (1954) wrote: "Theoretically, assuming no preferred orientation, self-absorption, or equipment factors, and with adequate counting statistics, the ratios of the respective principal peaks of calcite and aragonite should vary linearly with the relative percentage of these minerals." As yet, however, all the interfering factors have not been eliminated and the accuracy of the method is about ± 10 percent.

Equipment.—X-ray diffraction data were obtained by use of a General Electric XRD-3 proportional counter diffractometer. Patterns were run at a scanning rate of 0.2 degree 2θ per minute so that sufficient detail was available for interpretation. A 1° beam slit, 0.2° detector slit, and nickel-filtered copper radiation were used. The unit was

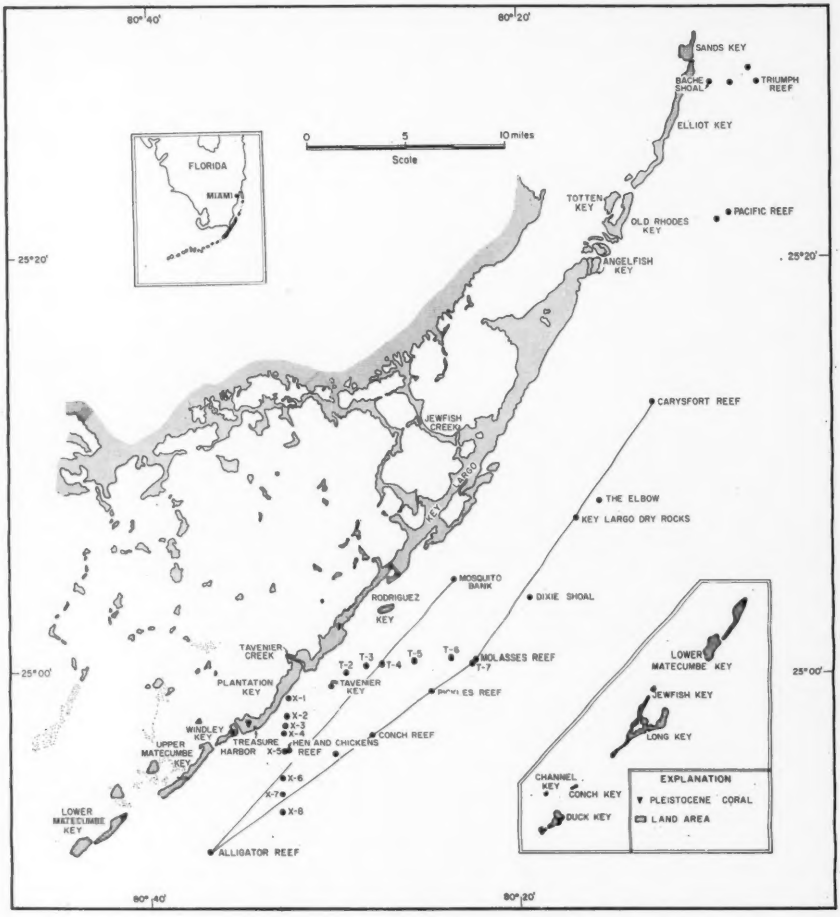

FIG. 1.—Locations of collecting stations, Florida Reef area.

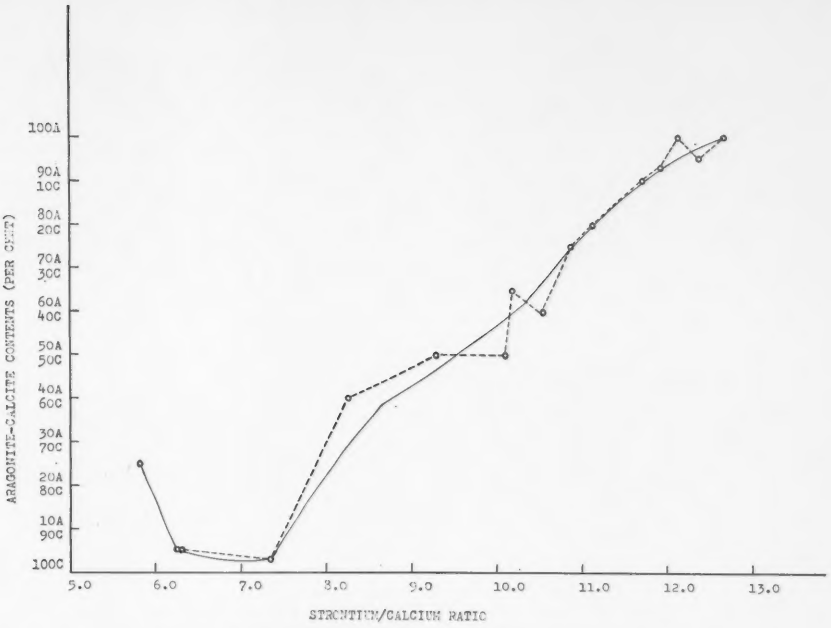

FIG. 2.—Aragonite-calcite contents of Pleistocene coral samples vs. their respective strontium-calcium (Sr/Ca).

operated at 48 kv and 15 ma.

X-ray mount preparation.—A thin layer of grease (Dow Corning High Vacuum Grease) was spread evenly on a glass slide and a powdered sample, minus 60 mesh, was passed through the mesh directly onto the greased slide. The excess powdered material was removed by gentle tapping. Using this technique of slide preparation instead of a packing technique, any error due to preferred orientation was probably eliminated.

Standardization patterns.—A series of standard mixtures of aragonite and calcite were prepared using as end members pure aragonite from a large *Porites furcata* (Recent coral) skelton and pure calcite from Joplin, Missouri. The standard mixtures were ground to pass a 60 mesh screen and were thoroughly mixed. Two patterns were run on each mixture and peak height measurements were made on the major reflection of each mineral on the recorder chart; these were the aragonite *d*-spacing of 3.40 Å, and the calcite *d*-spacing of 3.03 Å. Patterns of the unknowns were compared with those of the standards to determine their aragonite-calcite contents.

Since aragonite will convert to calcite slowly through exposure to air (Lowenstam, 1954), the samples studied were run within eight months of the time they were collected. This meant that any conversion which might have taken place probably fell within the ±10 percent accuracy of the method.

RESULTS AND CONCLUSIONS

Analyses of the Pleistocene corals (table 1) revealed significant variations in their strontium contents. The range of strontium content was 0.499 to 1.070 percent, or translating this into the more familiar geochemical terminology, the strontium:calcium ratio (Sr/Ca) ranged from 5.83 to 12.68. For comparison it should be noted that the aver-

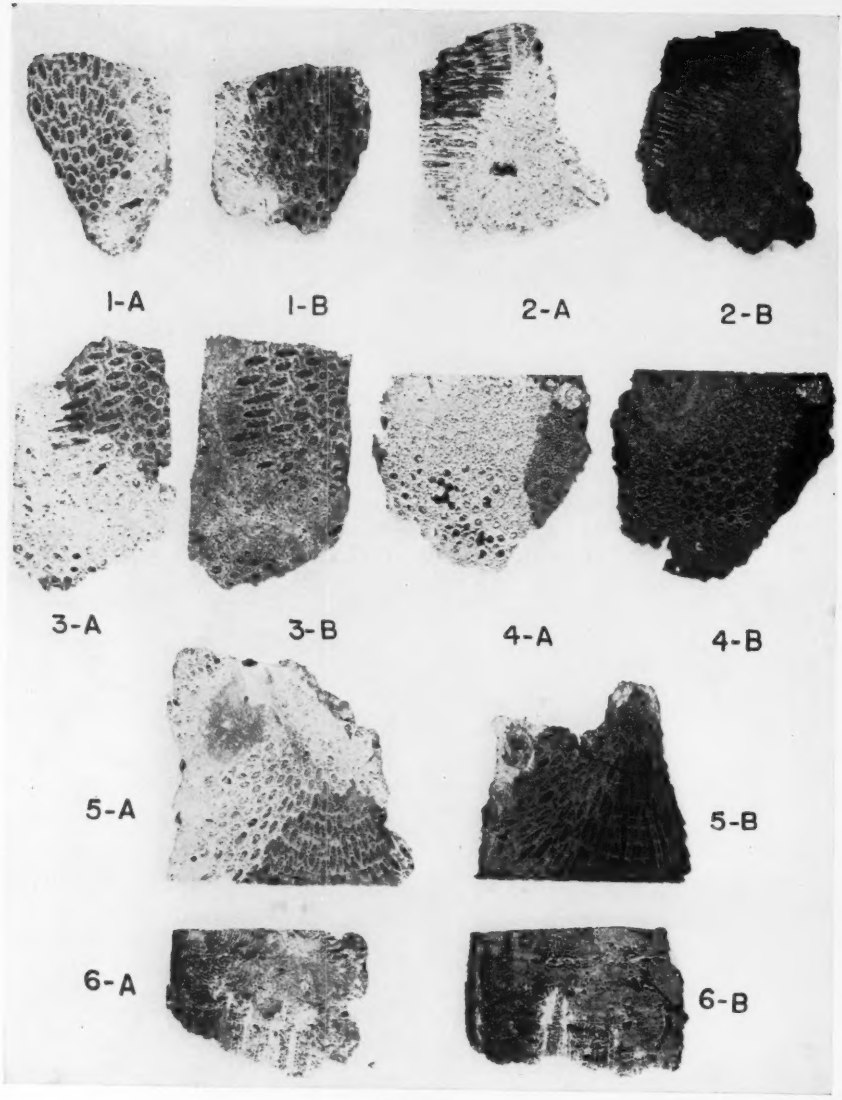

PLATE 1

age Sr/Ca ratio of 43 Recent coral specimens from the living reef to the east, 100 percent aragonite, was 12.65; the average strontium content was 1.055 percent (Siegel, 1958).

In an effort to discover a qualitative relationship between the Sr/Ca ratios and the aragonite-calcite contents, the coral sections were cut and stained. Stained sections showing a high aragonite content had a correspondingly high Sr/Ca ratio; where the stains indicated calcite was the dominant carbonate phase present, the Sr/Ca ratios were low; intermediate Sr/Ca ratios were correlated with intermediate aragonite-calcite values (table 1). More interesting was the fact that in several cases it was noted that one portion of a stained section was aragonite but that the adjacent portion of the same section was calcite (plate 1). Chemical analyses of adjacent sections (table 2) showed that in every case examined the Sr/Ca ratio of the aragonite portion of a section was about twice that of the calcite portion of the same sample.

Quantitative X-ray analyses of the samples confirmed the validity of the stains and revealed the quantitative relationship between the Sr/Ca ratios of the samples and their respective aragonite-calcite contents which is plotted diagrammatically in figure 2. Figure 2 demonstrates the definite relationship which exists between the Sr/Ca ratios and the degree of alteration to calcite. If we compare the Sr/Ca ratios of Recent corals (12.65 average) to those studied here, it is clear that whenever strontium is present in amounts which indicate that none or very little of it has been removed from the original aragonite, for example by ground water leaching, the inversion to calcite has hardly begun. In direct contrast, however, where the amount of strontium has been appreciably diminished, the alteration from aragonite to calcite has proceeded to a point which appears to be directly related to the degree of removal of strontium.

From these data it is evident that the strontium content of aragonitic material should be considered when discussing the kinetics involved in the alteration process. It is suggested that the presence of strontium, not as $SrCO_3$ but rather in substitution for calcium in the aragonitic crystal lattice, is an inhibiting factor which prevents or slows the

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EXPLANATION OF PLATE 1

All figures ×0.56

FIG. 1-A. *Montastrea* sp. No. 7. Cobalt nitrate stained section. Aragonite is darker area, calcite is light area.

FIG. 1-B. *Montastrea* sp. No. 7. Silver nitrate-manganous nitrate stained section. Aragonite is dark area, calcite is light area.

FIG. 2-A. *Montastrea* sp. No. 6. Cobalt nitrate stained section. Aragonite is dark area, calcite is light area.

FIG. 2-B. *Montastrea* sp. No. 6. Silver nitrate-manganous nitrate stained section. Aragonite is darkest area, calcite is lighter area.

FIG. 3-A. *Montastrea* sp. No. 16. Cobalt nitrate stained section. Aragonite is dark area, calcite is light area.

FIG. 3-B. *Montastrea* sp. No. 16. Silver sulfate-manganous sulfate stained section. Aragonite is darker section, calcite is lighter section.

FIG. 4-A. *Montastrea* sp. No. 9. Cobalt nitrate stained section. Aragonite is dark area, calcite is light area.

FIG. 4-B. *Montastrea* sp. No. 9. Silver sulfate-manganous sulfate stained section. Aragonite is darkest area, calcite is lighter area.

FIG. 5-A. *Montastrea* sp. No. 9. Cobalt nitrate stained section. Aragonite is darker area, calcite is light area.

FIG. 5-B. *Montastrea* sp. No. 9. Silver sulfate-manganous sulfate stained section. Aragonite is darker area, calcite is lighter area.

FIG. 6-A. *Diploria* sp. No. 14. Cobalt nitrate stained section. Aragonite is darkest area, calcite is lighter area.

FIG. 6-B. *Diploria* sp. No. 14. Silver nitrate-manganous nitrate stained section. Aragonite is darkest area, calcite is lighter area.

rate of inversion under natural geologic conditions, and only when much of the strontium has been removed may the alteration take place. It had also been suggested to the author that the alteration took place first and the strontium was merely kicked out; however, personal communications with Dr. Farrington Daniels of the Chemistry Department of the University of Wisconsin infer that in order to satisfy the kinetic relationships involved, the strontium might first have to be removed before the alteration can proceed.

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FIGS. 1–6, JUNE, 1960

THERMOLUMINESCENCE IN BIOGENIC CALCIUM CARBONATE[1]

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ABSTRACT

Radio-thermoluminescent potential of calcareous shell material is a function of $CaCO_3$ polymorphism. Calcitic fossils have a high capacity for thermoluminescent energy storage. Aragonitic shells are inert with respect to radio-thermoluminescence. Aragonite, however, emits luminescence when it reverts to calcite at approximately 425°C. This light is believed to be a triboelectric discharge associated with the sudden reconstructive phase change.

The shells belonging to a given taxonomic category tend to have similar and sometimes diagnostic thermoluminescent properties. Thermoluminescent correlation and age-dating of limestones must consider the consequences of biomineralogy and its accompanying thermoluminescence.

INTRODUCTION

The parameters of a solid which determine its thermoluminescent properties are generally but imperfectly known. In the case of $CaCO_3$ previous workers have outlined several important factors concerning its thermoluminescent capacity and variability (Zeller, 1954; Lewis, 1956; Medlin, 1959). As an additional contribution, a systematic survey was undertaken to classify and relate the thermoluminescence of biogenic $CaCO_3$ with specific crystallographic or mineralogic qualities. Biogenic $CaCO_3$ in the form of fossil and recent shell material was utilized as a convenient source of calcite, aragonite, and vaterite. Organically derived $CaCO_3$, moreover, is a common component of sedimentary rocks of diverse age, gross lithology, and geographic distribution. The full range of these variables and the effects they exert on thermoluminescence were therefore an intrinsic part of the survey.

THERMOLUMINESCENCE DEFINED

In brief, thermoluminescence is an exoenergetic radiation phenomenon possessed by certain materials, usually solids, which occurs during thermal stimulation. A closely related phenomenon is radio-phosphorescence. Both of these luminescent effects are attributed to the radiative transition of metastable, excited electrons. Thermoluminescence is logically classified as a temperature dependent case of phosphorescence. It may be considered residual phosphorescence which is unavailable at normal temperatures but recoverable by heating. Trapping or stabilizing of the excited electrons by some means is implicit.

Thermoluminescence is distinct from incandescence although both again involve electron transitions. Any solid will incandesce when heated enough, but not every solid will thermoluminesce. For practical purposes, however, thermoluminescence is indistinguishable from incandescence above red heat temperature. In this sense, thermoluminescence may be referred to as "cold light".

The potential for thermoluminescence in a crystal must be differentiated from its actual manifestation—especially in materials of geologic antiquity. By definition thermoluminescence requires *excited* electrons. Therefore exposure to an ionizing force is inferred. However, in this survey only the thermoluminescent potential of calcareous fossils is considered and not the degree of realization under geologic or synthetic circumstances. In other words, only the existence and depths of electron traps in fossils are explored.

The thermoluminescence discussed is short wave radiation induced or radio-thermoluminescent except when otherwise noted. Also, for purposes of this paper, thermoluminescence is qualitatively defined as the visible band from 3000 to 6000 angstroms. The photo tube used (RCA-1P21-S4) is especially responsive to the 3500 to 4500 angstrom band (blue-violet). Therefore, infrared, ultraviolet, or other non-visi-

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ble emissions are excluded from this definition although they may be present.

EXPERIMENTAL

Apparatus.—The equipment and operating procedures employed are described in detail by Ammentorp (1957). In brief, an electric-electronic device detects, measures, and records the luminescent emission from a heated sample. This particular system utilizes a new "flash-heating" feature which greatly enhances sensitivity to and resolution of thermoluminescent emission. As an output the device traces a plot of luminescent intensity (ordinate) against temperature of emission (abscissa). This curve is the graphic representation of the thermoluminescent character of the associated sample. The glow curve, as it is usually designated, for a particular sample with a specific state of excitation is reproducible.

Thermoluminescence is evaluated through use of glow curves. Relative or absolute data may be obtained including electron trap depth (temperature), rate of electronic transition (luminescent intensity), and electron storage capacity (integral of glow curve). For purposes of this study relative information is entirely adequate. Empirical comparison of glow curves was sufficient therefore for discriminating likenesses and differences in thermoluminescence.

Temperature calibration.—Time-temperature curves for various furnace power settings were empirically compiled. Heat sensitive crayons ("Tempilstiks," Tempil Corp., N. Y.) which melt at predetermined temperatures were used as reference points. Although these curves are internally consistent with the crayon series, their relation to real temperatures is uncertain because of subjective factors. The very rapid heating rates employed (20° to 30°C per sec) make the instant of exact crayon melting a difficult judgement. On the other hand, the fast heating rate also causes a nearly linear time-temperature curve, thus serving to limit error. As a general rule the temperature at which a given trap will eject its electrons will increase slightly with increasing heating rate. For example, a trap that apparently empties at a fundamental 140°C with a heating rate of 10°C per sec will empty at a fundamental 150°C when the heating rate is raised to 20°C per sec.

Irradiation procedure.—As previously stated, quantitative thermoluminescence is not one of the factors considered here. However, the recording of a glow curve implies some minimum amount of prior excitation. Because of the disparities between samples in age and in thermoluminescent energy accumulation rates, the amount of natural thermoluminescence in most samples was insufficient for registering a complete glow curve. Therefore, to energize all samples to a practical level of saturation a Co_{60} gamma ray source was employed (Saunders, Morehead, and Daniels, 1957). An exposure to approximately 50,000 roentgens, ample to reinforce the existing natural thermoluminescence and bring the glow curves to equilibrium with respect to further saturation, was found by trial and error. After irradiation and before actual glow curve determination, the samples were kept at dry ice temperature (−79°C) and in a dark container to prevent inadvertent thermal or photo stimulation.

Sample preparation.—One hundred seventy-six well preserved fossils were assembled, identified, and tested for thermoluminescence. Obviously dolomitized or otherwise drastically altered fossils were considered no longer typical organic remnants and therefore not used. However, a limited range of alteration between specimens was desired as an indicator of the tolerance and sensitivity of thermoluminescence to geologic processes. The consequence of the need for relatively "clean" fossils resulted in a collection of predominately post Jurassic forms. Nevertheless, several specimens were included to extend the range of the collection from Cambrian to Recent. Individual specimens came from a variety of locations around the world. A taxonomic summary of the collection is listed in table 1.

General procedure.—Exact operational procedures are detailed in the references cited above. Essentially, however, a known volume of powdered sample is irradiated and then heated before a photo-multiplier tube. The photo tube output is amplified and fed to a high speed recorder.

Because of standardized techniques and

TABLE 1.—*Identification and number of fossils analyzed for thermoluminescence*

Algae (3)
- Corallinaceae (2)
  - *Lithothamnion* (1)
- Chlorophyceae (1)
  - *Halimeda* (1)

Protozoa (2)
- Foraminifera (2)

Coelenterata (19)
- Zoantharia (19)
  - *Acrophelia* (3)
  - *Platytrochus* (2)
  - *Favosites* (2)
  - *Heliophyllum* (2)
  - *Streptelasma* (2)

Bryozoa (15)
- *Archimedes* (3)

Brachiopoda (13)
- Articulata (13)
  - *Schizophoria* (3)
  - *Douvillina* (3)
  - *Mesolobus* (2)

Mollusca (82)
- Scaphopoda (3)
  - *Dentalium* (3)
- Cephalopoda (4)
- Gastropoda (25)
  - *Turritella* (8)
  - *Natica* (2)
  - *Conus* (4)
  - *Olivella* (3)
  - *Trochus* (3)
- Pelecypoda (50)
  - *Crassatillites* (2)
  - *Glycymeris* (2)
  - *Vernericardia* (3)
  - *Cardium* (4)
  - *Pecten* (8)
  - *Ostrea* (5)
  - *Exogyra* (2)
  - *Macoma* (3)
  - *Anomia* (2)

Echinodermata (47)
- Cystoidea (2)
- Blastoidea (3)
  - *Pentremites* (2)
- Echinoidea (2)
- Crinoidea (40)

frequent calibration, all known variables are controlled. Any unsuspected variable introduced with the procedures is assumed to be constant and therefore still compatible with a valid, comparative analysis. Practically then, the only factors contributing to the character of a glow curve are the structure and crystallography of the sample itself.

BIOMINERALOGY

Vinogradov (1954) demonstrates that the composite chemical composition of all marine organisms would encompass virtually every natural element. However, the most frequent combinations in shell material in order of decreasing abundance are: $CaCO_3$, $MgCO_3$, $SrCO_3$, $BaCO_3$, SiO_2nH_2O, $CaSiO_4$, various hydroxides, $MnCO_3$, $FeCO_3$, $Al_2(CO_3)_3$, spongin, cornein, and chonchiolin. Furthermore, excluding the silica and scleroprotein integumented forms; $CaCO_3$ and $MgCO_3$ are the only components of any quantitative importance. With respect to thermoluminescence the remaining elements may be assigned to an impurity status. As a consequence, the thermoluminescent properties of the typical calcareous fossil are ascribed primarily to the $CaCO_3$ lattice. Impurities, dislocations, and boundary conditions may superpose variations on the basic $CaCO_3$ structure and influence the glow curve accordingly.

The compound $CaCO_3$ may occur naturally in its polymorphic forms of calcite I, aragonite, and vaterite. All forms appear in biologic skeletons. Crystalline habit and orientation comprise fundamental biocharacters in the classification of shell bearing organisms. The microscopic crystal fabrics of tests and shells have been successfully used to characterize and distinguish various animals on a generic or specific level (for example see Boggild (1930) and Cummings (1956)). These facts imply the inherent capability of biomineralogy for selective ionic concentration. Table 2 summarizes one aspect of this discrimination, the calcite-aragonite content of pertinent taxonomic categories.

SUMMARY OF DATA AND GENERAL CORRELATIONS

The thermoluminescence of biogenic $CaCO_3$ may be broadly classified into two groups. In its simplest terms, either a fossil may be highly radio-thermoluminescent or non-radio-thermoluminescent. Very few intermediate cases were encountered.

A perfect correspondence occurs between

TABLE 2.—*Characteristic polymorphic constitution of calcareous skeletal material*

Calcite	Calcite-aragonite mixture	Aragonite
Algae Corallinaceae	Mollusca Gastropoda (rare cases) Cephlopoda Pelecypoda Pectinacea	Algae Chlorophyceae
Protozoa Foraminifera		Coelenterata Zoantharia
Mollusca Pelecypoda Anomiacea Ostreacea		Mollusca Gastropoda Scaphopoda Pelecypoda
Bryozoa		
Brachiopoda Articulata		
Echinodermata		

the existence of thermoluminescence and calcite-aragonite content of each fossil. Those forms which exclusively secrete calcite, such as the echinoderms and the bryozoans, possess a large thermoluminescent potential. The purely aragonitic forms, such as the corals and gastropods, are non-thermoluminescent. A few organisms have the remarkable capacity for depositing selectively both calcite and aragonite in their shells. These fossils consequently reflect an intermediate degree of thermoluminescent capacity. Extending these observations, the thermoluminescent potential of an animal group may be predicted on the basis of crystal phases present. Conversely, the polymorphic constitution of a shell group may be derived from its thermoluminescent properties (table 2).

Geologic age has no effect on the non-thermoluminescent quality of biogenic aragonite as long as the aragonite structure is maintained. If secondary processes recrystallize the aragonite partially or completely inot calcite, a corresponding change is reflected in thermoluminescence.

The prime importance of the calcite-aragonite ratio on thermoluminescence was further confirmed by artificially growing the polymorphs of $CaCO_3$ (Wray and Daniels 1957), verifying with X-ray, and testing for thermoluminescent capacity. As in natural shell material the pure aragonite is non-thermoluminescent while calcite is highly thermoluminescent. The only radio-thermoluminescence found in aragonite was traced to calcite contamination. Vaterite, like aragonite, possesses no thermoluminescent capacity.

It is significant to note at this point that biogenic aragonite was observed to fluoresce to the same degree as biogenic calcite. In this event it may be concluded that electron energy in aragonite is not dissipated through radiationless "phonon" transitions but in radiative "photon" emissions. Apparently the aragonite structure has an electronic configuration such that fluorescence may occur but persistent high temperature electron traps are impossible.

As a first approximation the potential for thermoluminescence in a given calcareous shell is directly proportional to the calcite content of that shell. Within various calcites, however, thermoluminescence may vary qualitatively. In other words, the glow curve for calcite may take on different shapes. Mechanical pretreatment, radioactive content, age, impurities (substitutional and interstitial), crystal size, and perfection all operate to modify both naturally and artificially induced thermoluminescent properties. Nevertheless, several generalities do exist concerning the shape of the biogenic $CaCO_3$ glow curve or specifically the biogenic calcite glow curve. Such calcites may have one or two radio-thermoluminescent "peaks", that is light pulses, on their glow curves corresponding to two discreet electron trap depths. When heated at a constant 1°C per sec, these peaks occur at 110°C and 240°C. With the "flash-heating" technique they correspond to approximately 150°C and 250°C respectively. The 150°C peak is omnipresent in all grades and ages of calcite and is therefore inherent to the calcite lattice. The 250°C peak may be absent or may vary in height relative to the 150°C peak.

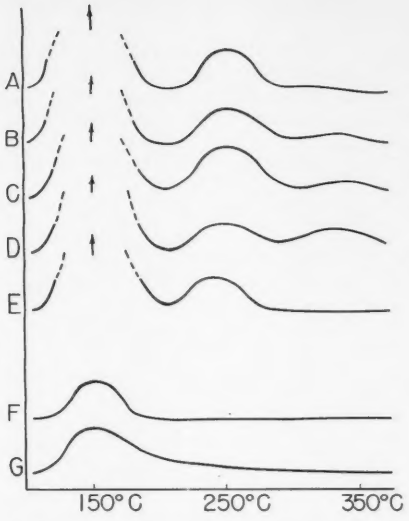

FIG. 1.—Echinoderm glow curves. Dashed lines indicate where high intensity peaks have run off scale in the originally recorded glow curves.

(A) Cystoid plate, Silurian, Beech River Formation, Tennessee.
(B) Cystoid holdfasts, Cambrian, Morgan Creek Limestone, Texas.
(C) *Pentremites*, Mississippian, unknown location.
(D) *Pentremites*, unknown location.
(E) *Cryptoblastus*, Mississippian, Burlington Limestone.
(F) Echinoid spines, Pennsylvanian, Altamont Limestone, Oklahoma.
(G) Sand dollar, Recent, California.

The presence of the 250°C peak is probably a consequence of structural modification produced by critical dislocations and/or incorporation of impurities into the host calcite structure. In addition a diffuse, low-intensity peak which occurs above 300°C is sometimes observed. In calcitic shells it is caused by a thermally stimulated form of chemiluminescence or triboluminescence initially induced by grinding (Debenedetti, 1958; Johnson and Daniels, 1959). In some cases it may be the high temperature peak associated with protodolomite (Lewis, 1956, p. 701); for example see figure 1.

As expected, these peaks appear in biogenic calcite in various relative magnitudes. Sub-variations imposed on the basic one or two peaks may be attributed to further minor structural changes (figs. 2 and 3). Chemical impurities in crystals are conventionally assigned the function of activating fluorescence as well as inducing electron traps. However, ease of electron excitation, in this case susceptibility to fluorescence, does not necessarily imply the co-existence of high temperature thermoluminescence (Urbach, 1948, p. 450). The complicated interactions between these luminescent effects and the abundance of impurities in biogenic calcite makes the designation of specific activating chemicals difficult. Nevertheless, divalent Mn is a known activator of fluorescence in calcite (Fonda, 1940) and has been proposed as the primary activator of thermoluminescence in limestone (Medlin, 1959, p. 457).

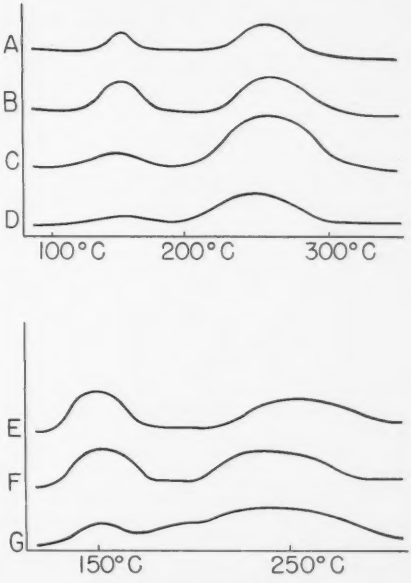

FIG. 2.—Bryozoan glow curves.

(A) Encrusting bryozoan, Recent, California.
(B) Mixed bryozoans, Devonian, Lime Creek Shale, Iowa.
(C) "Button" bryozoans, Ordovician, Platteville Formation, Wisconsin.
(D) Encrusting bryozoan, Ordovician, Platteville Formation, Wisconsin.
(E) *Archimedes*, Mississippian, unknown location.
(F) *Archimedes*, Mississippian, Alabama.
(G) *Archimedes*, Mississippian, Warsaw Limestone, Missouri.

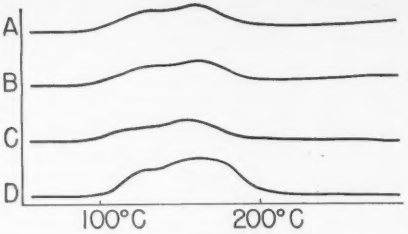

FIG. 3.—Glow curves of *Pecten*.

(A) Pleistocene, Florida.
(B) Tertiary, unknown location.
(C) Pleistocene, California.
(D) Pliocene, California.

TRANSITION LUMINESCENCE OF ARAGONITE

In biogenic aragonite and in laboratory grown crystals of aragonite no radiation dependent thermoluminescence was found. However, a positive light emission was observed concurrent with the solid-solid, reconstructive phase transition of aragonite into calcite at temperatures above 400°C. This luminescence is closely allied with or analogous to the crystallization induced thermoluminescence of Zeller, Wray, and Daniels (1955).

Since the aragonite to calcite transition is endothermic, the associated light is not typical chemiluminescence (Bowen, 1946, p. 267). More likely it is a form of triboluminescence involving the breaking of bonds and rearrangements of atoms related to the transition (Kozu and Kani, 1934). Triboluminescence is attributed to triboelectric excitation in rapidly disrupted crystals (Gross, Stranski and Wolff, 1955).

The glow curves of aragonitic shells clearly show broad peaks centered at 425°C corresponding to the transition luminescence (fig. 4). A plot of relative integrated transition luminescence (area under glow curve) against percent weight of aragonite produces a near linear curve (fig. 5). The sigmoidal shape is an instrumental error caused by electronic dampening of light intensity at the extreme limits of one recorder scale. Nevertheless, the amount of transition luminescence is still a simple function of aragonite/calcite ratio. An exposure to 500,000 roentgens of gamma radiation shows no perceptible effect in altering the quantity or quality of transition luminescence in aragonite. Applying this knowledge, the measure of transition luminescence in an unknown sample will determine the aragonite content of that sample.

CONCLUSIONS PERTAINING TO PALEONTOLOGY

Various degrees of glow curve consistency are present within taxonomic categories. Figure 3 shows the obvious thermoluminescent similarity among specimens of *Pecten* of differing age and distribution. Also the echinoderms and bryozoans possess different glow curve types (figs. 1 and 2). Of course, the persistent absence of thermoluminescence in corals and most mollusks forms a distinctive, if negative, glow curve (fig. 5). These similarities in thermoluminescent properties confirm the fact that the crystallography and mineralogy of shell material is not completely random.

To the extent that individual organisms inherit their biomineralogic traits, they also inherit the complementing thermoluminescence. Theoretically then, thermoluminescence may serve as a phylogenetic biocharacter in shell or skeleton bearing organisms. Disregarding the effects of sedimentary or diagenetic forces, the validity of thermoluminescent "fingerprints" will primarily depend on the levels of impurity tolerated by organic mineralization. Restated, it is the in-

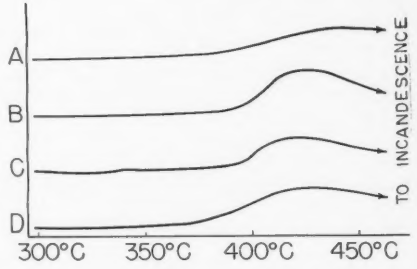

FIG. 4.—Glow curves of aragonitic shells.

(A) *Turritella*, Pliocene, Caloosahatchee Limestone, Florida.
(B) *Natica*, Miocene, Austria.
(C) *Saxicavia*, Recent, California.
(D) *Acrohelia*, Oligocene, Vicksburg Formation, Mississippi.

fluence that contemporary environment has on biomineralogy. Significantly, the status of the Ca/Sr and Ca/Mg ratios in calcareous shell bearing animals is in doubt. Zeller and Wray (1956, p. 141, 150–151) discuss these problems and cite the pertinent literature. Recently, Turekian (1959) has found that generic association is the primary control of trace element distribution in molluscan shells.

On the basis of the evidence in this survey, however, the applicability of thermoluminescence to fossil identification appears severely limited. At present only such broad categories as phyla and class seemingly can be separated by thermoluminescent properties. However, factors not included in this study, such as stage of ontogeny and precise, homologous sampling, may lower this threshold of discrimination.

A comparison between the glow curves of fossils and their matrix shows varying contrasts and similarities (fig. 6). Glow curves are congruent where fossils are interred in a similar coquina groundmass or are secondarily altered to a common mineralogic state. Because of the hazards to chemical and crystalline stability under sedimentary conditions a general amelioration or elimination of original thermoluminescent differences is effected with increasing age.

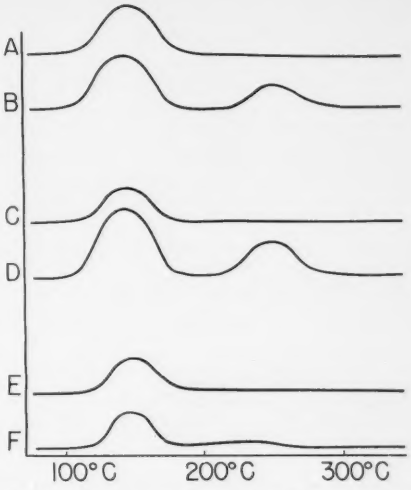

FIG. 6.—Comparison of glow curve between fossil and matrix.
(A) Crinoid stem, Ordovician, Galena Limestone, Wisconsin.
(B) Matrix of A.
(C) Crinoid stem, Devonian; Linwood, Iowa.
(D) Matrix of C.
(E) Crinoid arms, Mississippian; Gilmore City, Iowa.
(F) Matrix of F.

THERMOLUMINESCENCE OF LIMESTONE

Throughout geologic time, a major if not primary component of limestone has been organically derived $CaCO_3$. Since the thermoluminescence of organic $CaCO_3$ varies widely, it follows that the thermoluminescence of limestones should vary also as indeed they do (Saunders, 1953). The thermoluminescence of limestone is presumably subject to the same controls as in calcareous shells. The prime factor is the atomic configuration or the polymorphic form of the $CaCO_3$; secondly is the amount and kind of defects present. The thermoluminescence of a given limestone is the integration of the thermoluminescent properties of all its components, including fossils. In many limestones the resultant thermoluminescence would be the indirect measure of the biotope of that limestone. When the biotope changes laterally, the associated thermoluminescence would also change. An extreme example would be the thermoluminescent change between an aragonitic coral reef and an adjacent calcitic oyster bed, which is the difference between absence or presence of radiothermoluminescence.

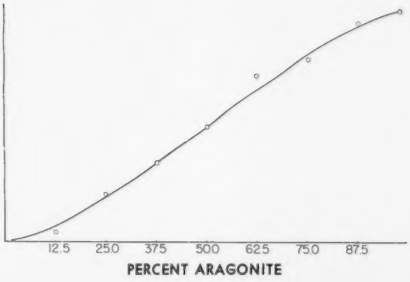

FIG. 5.—Calcite/aragonite ratio as function of transition luminescence.

Depending on real circumstancs, the correlation of limestones by thermoluminescence (Parks, 1953; Bergstrom, 1956; Pitrat,

1956) may then be subject to organic controls. In strictly bioclastic limestones thermoluminescence is directly related to the properties of the biotope of that rock. Of course, this would be true of any gross physical measurement such as electric, gamma, or sonic logging. In any event, thermoluminescent correlations are possible only in chemically and crystallographically uniform rocks. Otherwise, continuous sampling is necessary to detect gradational or sudden changes. In practice, thermoluminescent uniformity or change may correspond to biofacies.

The biotope of a limestone also has an effect on the problem of thermoluminescent age dating. This technique utilizes thermoluminescent energy storage and thermoluminescent energy accumulation rates to index absolute age of a rock (Zeller, Wray, and Daniels, 1957).

Since an aragonitic biotope would contribute nothing to the accrued thermoluminescence of a limestone, it plays a neutral or even negative role. Aragonite is metastable at all temperatures and pressures of the geothermal gradient (Jamieson, 1953, p. 1389). At any time, therefore, it is subject to transition to the stable calcite form whenever sufficient activation energy is available. This event may or may not occur in the course of geologic time. Converted aragonite if present, will be "out of phase" with its contemporary calcite with respect to thermoluminescent energy accumulation. Thermoluminescent age dates based on such samples will have a built-in error. To avoid this uncertainty, exclusively calcitic fossils could be used as a uniform and original source of calcite.

With present techniques, aragonitic limestones are basically unfit for age-dating by thermoluminescence. It has been shown that transition luminescence of aragonite is independent of age or radioactivity. Aragonitic limestones will show in part a fixed supply of quantitative thermoluminescence regardless of age. In addition, during the heating process aragonite will be converted into calcite. Since the original sample is thus destroyed, the necessary calibrating by artificial irradiation (Zeller, Wray, and Daniels, 1957, p. 124) will be invalid.

SUMMARY

From the analysis of more than 900 glow curves polymorphism was found to be the primary control of thermoluminescence in $CaCO_3$. Calcite has thermoluminescent potential while aragonite and vaterite are completely devoid of radio-thermoluminescence. All biogenic calcites, including relatively pure ones, have a natural electron trap at about 150°C. In addition calcite shows the propensity for one more major trap depth of about 250°C which probably is induced by the structural modification of impurities. Another minor trap above 300°C may be caused by protodolomite or grinding induced thermoluminescence. In general the overlapping of temperature limits and/or exotic defects may vary the glow curves of biogenic calcite infinitely within the basic two-peak pattern. A radiation independent luminescent phenomenon, probably triboluminescence, accompanies the transition of aragonite into calcite at about 425°C. The thermoluminescent properties of individual calcareous fossils tends to conform to a pattern typical of the race. Age tends to equate the thermoluminescent differences between fossils in one sedimentary environment.

ACKNOWLEDGMENTS

The writer wishes to express his gratitude to Dr. Stanley Tyler, whose original ideas and stimulating lectures inspired this research. Thanks are also due to Dr. Farrington Daniels for his guidance and technical assistance. The recent shell collection of Mr. Wendell Gayman of Scripps Institute of Oceanography is gratefully acknowledged and appreciated. The work was supported with funds from the Standard Oil Company of Texas and the Wisconsin Alumni Research Foundation through the Research Committee of the Graduate School, University of Wisconsin.

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FIG. 1, JUNE, 1960

DYE-STAINING TECHNIQUE FOR EXAMINATION OF SEDIMENTARY MICROSTRUCTURES IN CORES[1]

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ABSTRACT

A dye-staining technique is described that is capable of producing a high visible contrast between different lithologies in core-samples; this enables microstructures in the sediment to be clearly identified and illustrated.

INTRODUCTION

Some of the most valuable data obtainable from core samples are provided by the microstructures of the sediments. Although a great deal can usually be learned from the general nature of the sediment and from any obvious variations within it, the microstructures are important in themselves and are frequently critical in the interpretation of the history and mode of deposition of the sediment. This is particularly true of shelf sediments, which are sometimes highly variable and which often contain organic burrows or laminations (fig. 1, A, B, C). Unfortunately, these structures are frequently so indistinct that it is difficult to describe or illustrate them in a satisfactory manner. They can sometimes be clarified photographically by the use of high-contrast plates and paper, but it is obviously desirable to have some method of treating the sample which will increase the visible contrast between the various lithological microunits. The present paper is an account of a method which the writer has found useful on the range of core samples tested.

METHOD

The core is dried or allowed to dry out, and a flat surface is cut with a scalpel on one side of the core, along its entire length. With a 2-inch diameter core, a flat 1 in wide surface may be obtained with the loss of only 3 percent of cross-section. Any smeared or contaminated material on the outside of the core is thus removed, and the general lithology of the core can be readily determined by examining the flat surface. Representative portions are then selected and removed for the determination of microstructures; this is generally easy since most cores develop numerous transverse shrinkage cracks. A sub-sample 2–3 in long is suitable for a 2 in diameter core. The flat surface of the subsample (fig. 1, A, B, C) is then rendered as smooth as possible by running the specimen down a carpenter's plane which is most conveniently inverted and clamped in a vice. If the core contains coarse fragments of any kind which pluck out and score the surface, it may be necessary to moisten the surface and complete the flattening process with a razor blade.

The specimen is then laid horizontally on the bench with the flat surface uppermost; the surface is moistened evenly with water, and a solution of strongly-coloured dye is applied as evenly as possible. This can be done with a soft paint-brush, with a pad of porous material soaked in the dye, or with an ink-roller. The specimen is left for a few minutes to allow the dye to soak in, and the coloured surface is then gently shaved with a razor blade or a scalpel. In some cases, the best results are obtained if the specimen is first dried at about 80°C.

It will be found that the dye has soaked into the sediment for a short distance, of the order of 2–3 mm, but has penetrated further into the more permeable parts of the sediment than into the less permeable parts. When a critical thickness has been removed, the least permeable material will regain its original colour, all of the dye-stained layer in this material being gone. The more permeable, however, will still be coloured by the

[1] New Zealand Oceanographic Institute Contribution No. 79. Manuscript received September 9, 1959.

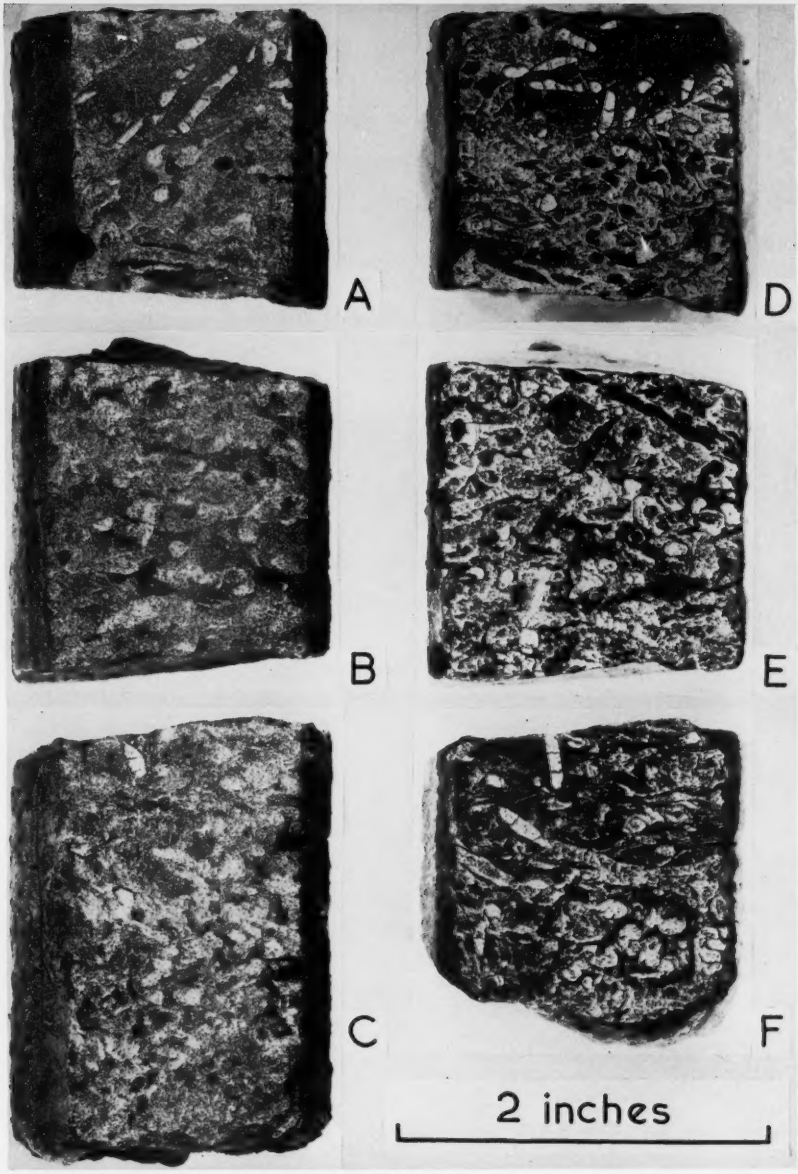

FIG. 1.—Three adjacent sub-samples from core MT/1, untreated (A–C) and treated with methylene blue (D–F). The portion shown in F represents only the upper part of the untreated sub-sample C.

The photographs were taken under the following conditions. Untreated sub-samples: thin-film panchromatic half-tone R50 plate, soft print. Treated sub-samples: fine-grain panchromatic R25 plate, normal print. Photographer: H. D. O'Kane, New Zealand D.S.I.R.

dye, and the full dye colour will remain in the most permeable parts of the sediment. Variations in permeability are thus rendered conspicuous by variations in the colour of the shaved surface. It is important, of course, not to shave away too much material because the dyed layer will be removed altogether.

In general, the sandy parts of the core will be comparatively permeable and the muddy parts impermeable so that on the treated surface the sandy parts are dye-coloured and the muddy parts are sediment-coloured (typically light to medium grey). Any microstructures involving differentiation of the sandy and muddy components in the sediment are thus rendered clearly visible (fig. 1, D, E, F).

The method was originally tested on a short core of sandy mud (fig. 1, A–F) from Cook Strait, New Zealand; this core (MT/1) was taken from near the mouth of the Wairau River in about 10 fathoms. A number of dyes were tried, some in aqueous and others in alcoholic solution; the results varied widely from one dye to another, as shown in table 1.

There is an apparent tendency for the effectiveness of the dyes to increase from the red to the violet end of the spectrum, and this may be useful in the future as a guide in selecting additional dyes for the process. Although many more dyes would have to be tested to find out whether this tendency is a general one, it seems possible that the type of molecular configuration which gives rise to a blue or violet colour also allows the dye to be rapidly adsorbed on clay particles. This effect would tend to inhibit the penetration of the dye into fine-grained sediment, and would thus increase the contrast between the finer and coarser parts of a core sample. It has already been shown by Gieseking and Jenny (Grim, 1953, p. 251) and by Robertson and Ward (Grim, 1953, p. 273) that many clays have a strong affinity for methylene blue.

TABLE 1. *Results obtained with various dyes*

Dye	Medium	Contrast
Aniline Blue	Water	Poor
Brilliant Green	Alcohol	Moderate
Crystal Violet	Water	Good
Carbol Fuchsin	Water	Poor
Eosin	Alcohol	Poor
Methyl Green	Alcohol	Fair
Methyl Violet	Water	Fair
Methyl Violet	Alcohol	Moderate
Methyl Violet 6B	Water	Good
Methylene Blue	Water	Good
Neutral Red	Water	Poor
Nigrosine	Water	Poor

There is a great deal of scope for further investigation, since many hundreds of dyes are available which might profitably be tested for comparison against a standard type of sediment. Even when a list of the most useful dyes has been compiled, it may be necessary for a core under investigation to be tested with several dyes to find the most suitable one for that particular sample. Because crystal violet, methyl violet 6B, and methylene blue are the best among the dyes so far tried by the writer, it does not mean that they will be the best in every case.

This method has been applied to the examination of a series of cores from open shelf areas around New Zealand, and it is apparent that organic burrows are the most common microstructures in these sediments, well-developed lamination being rare.

Techniques involving the impregnation of the sample with wax or resin, and the subsequent sectioning of the treated material, are in customary use in various laboratories in Europe and U.S.A. The dye technique described here, however, normally produces a higher visible contrast than is obtainable with impregnation methods. The dye technique is also rapidly applied, uses only a small volume of material, and does not contaminate the remainder of the treated sample.

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JUNE, 1960

NOTES

OCCURRENCE OF ALKALI METALS IN SOME GULF OF MEXICO SEDIMENTS: AMENDED RUBIDIUM VALUES AND K/Rb RATIOS[1]

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In the December 1958 issue of the *Journal of Sedimentary Petrology*, Welby has published determinations of the alkali elements in sediments from the Gulf of Mexico. The purpose of this note is to draw attention to a systematic error in the values reported for rubidium. This element was determined by a spectrochemical procedure, and "a standard granite (G-1) and diabase (W-1) (Fairbairn and others, 1951) were used as basic standards for sodium, potassium, and rubidium" (Welby, 1958, p. 433). When these determinations were made in 1952, the recommended values for Rb in these standards were 570 ppm (.057%) for the granite, G-1, and 64 ppm (.0064)% for the diabase, W-1 (L. H. Ahrens, personal communication). Welby's results are based on these values. (Note that they are expressed as percent Rb_2O.)

Ahrens and Fleischer (in press) have recommended new Rb values for these standards based on more recent determinations by flame photometric (Horstman, 1956; Goldich and Oslund, 1956), isotope dilution (Herzog and Pinson, 1955; Smales and Webster, 1958), neutron activation (Cabell and Smales, 1957), and x-ray fluorescence techniques (Hower and Fancher, 1957). These determinations range from 205 to 248 ppm for G-1 and from 19 to 28.5 ppm for W-1. Ahrens and Fleischer (in press) recommend values of 224 ppm (.0224%) Rb for G-1 and 22 ppm (.0022%) Rb for W-1. These values are less than half the previous values used by Welby. On the basis of the agreement between these several independent methods of analysis, it is believed that the true values for Rb in these standards are within the limits given above, and that future changes in the recommended values will be small.

The results derived from spectrochemical analysis (and similar instrumental techniques) depend on the values assigned to the concentration of the element in question in the standard samples. Because the values of Rb in G-1 and W-1 used by Welby are now known to be too high, the Rb figures given for the sediments are systematically too high. However, it is possible to correct them to more acceptable values by multiplying them by 224/570[2] after first converting the Rb_2O figures to Rb.

Because of the geochemical and geochronological significance of Rb, and because the data might be used uncritically in computing average values for Rb in sediments, it has been thought desirable to recalculate Welby's data to conform with currently accepted Rb data. The results have been amended by converting the original Rb_2O figures to Rb (factor .9144) and reducing the Rb values by 224/570 (.3930). Both the original and the recalculated values are given in table 1, which corresponds to table 2 of Welby's paper, and table 2, which corresponds to Welby's table 11. The same sample order is used, and Welby's K_2O figures have also been converted to K (factor: .83013).

K/Rb Ratios

On pages 444–445, Welby (1958) discusses the K/Rb ratio and states that "the data presented in table 10 indicate that the

[1] Manuscript received July 15, 1959.

[2] This correction factor is based on the Rb values for G-1, which are considered to be more reliable for this purpose than those for W-1.

TABLE 1.—*Average values for K, Rb and K/Rb ratio for various environments. (Compare Welby 1958, table 2.) All average values have been calculated from the data in table 2 of this paper and are not recalculated from Welby's table of average values*

	No. of Samples	% K	% Rb Welby 1958	% Rb Recalculated	K/Rb Welby 1958	K/Rb Recalculated
VLB	12	1.51	.024	.0094	62	160
San Antonio Bay	4	1.58	.024	.0090	67	176
Rockport-Offshore	2[1]	1.35	.018	.0070	77	193
GR 7 PB	1	.349	.0073	.0029	48	120
Mississippi Delta	14	.754	.011	.0045	67	169
Globigerina Oozes	18[2]	1.85	.024	.0092	79	201
Gulf of Mexico (exclusive of oozes)	78	2.40	.034	.013	71	181
Composites	7	1.18	.015	.0059	78	200

[1] Sample J.35 A omitted from average because of low K/Rb ratio.
[2] Sample E.153 A omitted from average because of low K/Rb ratio.

potassium-rubidium ratio of an average igneous rock is 82 if the April 1952 value for the rubidium content of an average igneous rock is accepted. The average of the potassium-rubidium ratios of the sedimentary materials used in this investigation, exclusive of the composite samples, is 77." The average K/Rb ratio is approximately 230 (Taylor and others, 1956; Herzog and Pinson, 1956), and a recent estimate, based on this ratio, of the average Rb content of igneous rocks is 115 ppm (Ahrens and Taylor, 1960).

In figure 1 both sets of rubidium values are plotted on the K/Rb diagram due originally to Ahrens and others (1952). The average K/Rb line in this diagram was shifted to conform with the systematic shift in the Rb values by Taylor and others (1956). The limits of scatter of the data are based on approximately 1000 analyses of igneous and sedimentary rocks and minerals and meteorites and are taken to indicate the limits of "normal" K/Rb ratios. Taylor and others (1956), Taylor and Heier (1958a, 1958b), Heier and Taylor (1959) and Taylor and Ahrens (1959) discuss the geological significance of the normal K/Rb ratios and of "abnormal" or "anomalous" values of the ratio. Using the recalculated Rb data, the plots of K versus Rb fall within the "normal" limits of scatter with two exceptions. Sample EG 153 A is reported to contain .027 percent Rb which recalculates to .011 percent Rb (K/Rb ratios of 6.1 and 15.1 respectively; Point a in figure 1). Before this is accepted as a genuine case of Rb enrichment, both K and Rb determinations should be repeated. The same comment applies to sample J 35 A (Point b in figure 1). It can also be seen from figure 1, as well as from an inspection of the figures for the K/Rb ratios given in tables 1 and 2, that the K/Rb ratios are less than the average ratio of 230. Although they lie within the limits of scatter of normal K/Rb ratios, it is possible that slight Rb enrichment occurs. Many slight, but geologically significant, variations in the K/Rb ratio are probably concealed by a combination of sampling difficulties and lack of really precise analytical data (Heier and Taylor, 1959, p. 290).

TABLE 2.—*Results of spectrochemical analyses of sediments (Wt % corrected to 110° C), from Welby (1958) table 11. K_2O and Rb_2O figures and K_2O/Rb_2O ratios from Welby are expressed as % K, % Rb and K/Rb. The recalculated Rb figures and K/Rb ratios are given in Columns 3 and 5. Sample order is the same as in Welby (1958) table 11.*

	1	2	3	4	5
Sample No.	% K	% Rb Welby 1958	% Rb Recalculated	K/Rb Welby 1958	K/Rb Recalculated
Gulf of Mexico Samples					
EG 1-B	2.39	.036	.014	66	171
EG 1-C	2.42	.036	.014	67	173
EG 2-B	2.39	.038	.015	63	159
EG 2-C	2.37	.036	.014	66	169
EG 3-B	2.23	.038	.015	59	149
EG 3-C	2.19	.035	.014	63	156
EG 4-B	2.33	.035	.014	67	166
EG 4-C	2.11	.030	.012	70	176
EG 6-B	3.60	.045	.018	80	200

TABLE 2—*continued*

Sample No.	1 % K	2 % Rb Welby 1958	3 % Rb Recal-culated	4 K/Rb Welby 1958	5 K/Rb Recal-culated
EG 6-C	2.55	.037	.015	69	170
EG 9-A	2.42	.036	.014	67	173
EG 9-B	2.09	.029	.011	72	190
EG 9-C	2.51	.036	.014	70	179
EG 12-A	1.68	.030	.012	56	140
EG 12-B	2.22	.034	.013	65	171
EG 12-C	2.09	.030	.012	70	174
EG 15-A	2.08	.032	.013	65	160
EG 15-B	1.90	.027	.011	70	173
EG 15-C	2.39	.030	.012	80	199
EG 99-A	2.85	.037	.015	77	190
EG 99-B	2.84	.035	.014	81	203
EG 99-C	2.27	.027	.011	84	206
EG 103-A	3.17	.035	.014	91	226
EG 103-B	2.11	.025	.0097	84	218
EG 103-C	2.33	.029	.011	80	212
EG-105-A	3.03	.035	.014	87	216
EG 105-B	3.15	.037	.015	85	210
EG 105-C	3.08	.041	.016	75	193
EG 106-A	2.97	.035	.014	85	212
EG 106-B	2.86	.035	.014	82	204
EG 106-C	2.62	.035	.014	75	187
EG 107-B	2.35	.031	.012	76	196
EG 107-C	2.77	.032	.013	87	213
EG 108-B	2.83	.035	.014	81	202
EG 108-C	2.49	.032	.013	78	192
EG 109-B	2.91	.037	.015	77	194
EG 109-C	2.65	.031	.012	86	221
EG 111-A	2.45	.028	.011	88	223
EG 111-B	3.15	.033	.013	96	242
EG 111-C	2.49	.032	.013	78	192
EG 212-A	2.53	.032	.013	79	195
EG 215-A	2.56	.035	.014	73	183
EG 218-A	1.93	.030	.012	64	161
EG 221-A	.407	.0089	.0035	46	116
EG 225-A	.664	.015	.0057	44	116
WG-140-A	2.50	.037	.015	68	167
WG 140-B	3.10	.046	.018	67	172
WG 140-C	2.76	.035	.014	79	197
WG 145-B	2.57	.028	.011	92	234
WG 147-A	2.53	.036	.014	70	181
WG 147-B	2.77	.047	.018	59	154
WG 149-A	3.16	.039	.015	81	211
WG 149-B	2.69	.031	.012	87	224
WG 153-A	2.69	.033	.013	82	207
WG 153-B	2.47	.035	.014	71	176
WG 422-A	1.15	.018	.0071	64	162
WG 480-A	2.76	.034	.013	81	212
WG 485-A	2.94	.032	.013	92	226
WG 515-A	1.39	.020	.0079	70	176
WG 515-B	1.91	.032	.013	60	147
WG 515-C	2.46	.048	.019	51	129
WG 532-A	2.70	.058	.023	47	117
WG 532-B	2.39	.035	.014	68	171
WG 532-C	2.22	.034	.013	65	171
WG 538-A	2.42	.035	.014	69	173
WG 538-B	2.76	.052	.020	53	138
WG 542-A	1.56	.029	.011	54	142
WG 542-B	2.76	.037	.015	75	181
WG 542-C	2.53	.047	.018	54	141
WG 545-B	2.15	.033	.013	65	165
WG 545-C	1.89	.037	.015	51	126
WG 549-A	2.43	.044	.017	55	143
WG 549-B	1.23	.016	.0065	77	189
WG 549-C	2.20	.032	.013	69	169
WG 550-B	2.27	.027	.011	84	206
WG 550-C	2.12	.026	.010	82	212
WG 551-B	2.22	.033	.013	67	171
WG 551-C	2.39	.037	.015	65	159
Globigerina Oozes					
WG 545-A	3.69	.041	.016	90	231
WG 550-A	1.50	.018	.0072	83	208
WG 551-A	3.27	.038	.015	86	218
EG 1-A	1.97	.023	.0090	86	219
EG 2-A	1.66	.025	.0097	66	171
EG 3-A	3.10	.037	.015	84	207
EG 4-A	2.47	.035	.014	71	176
EG 6-A	2.27	.025	.0097	91	234
EG 107-A	2.16	.026	.010	83	216
EG 109-A	.515	.0073	.0029	71	178
EG 128-A	.68	.010	.0040	68	170
EG 137-A	2.71	.035	.014	77	194
EG 146-A	2.11	.029	.011	73	192
EG 149-A	.980	.016	.0061	61	161
EG 151-A	.523	.0080	.0031	65	169
EG 153-A	.166	.027	.011	6.1	15.1
EG 185-A	1.27	.019	.0075	67	169
EG 187-A	1.71	.019	.0075	90	228
EG 190-A	.789	.013	.0050	61	158
Mississippi Delta Samples					
MP 112-51	1.23	.018	.0072	68	171
ABL 130 cm					
MP 115-51	1.19	.018	.0072	66	165
ABL 130 cm					
MP 122-51	.747	.012	.0047	62	159
ABL 0 cm					
MP 123-51	.540	.0080	.0031	68	174
ABL 0 cm					
MP 123-51	.648	.011	.0043	59	151
ABL 40 cm					
MP 123-51	.224	.0037	.0015	61	149
ABL 130 cm					
MP 128-51	.390	.0063	.0025	62	156
ABL 0 cm					
MP 128-51	.581	.0084	.0033	69	176
ABL 130 cm					
MP 135-51	.921	.016	.0061	58	151
ABL 0 cm					
MP 135-51	.158	.0025	.00097	63	163
ABL 130 cm					
MP 137-51	.540	.0087	.0034	62	159
ABL 0 cm					
MP 137-51	.598	.0089	.0035	67	171
ABL 130 cm					
BS 107-51	1.64	.012	.0083	78	198
ABL 65–71 cm					
BS 107-51	1.15	.016	.0065	72	177
ABL 100–105 cm					
VLB Samples					
VLB 31c-9	1.59	.028	.011	57	145
VLB 31c-10	1.44	.023	.0090	63	160
VLB 31c-11	1.36	.022	.0086	62	158
VLB 43c-1a	1.49	.019	.0075	78	199
VLB 43c-2a	1.87	.022	.0086	85	217
VLB 43c-2b	1.97	.028	.011	70	179
VLB 43c-2c	1.27	.021	.0083	60	153
VLB 43c-3b	1.54	.026	.010	59	154
VLB 43c-4a	1.23	.024	.0093	51	132
VLB 43c-4c	1.49	.025	.0097	60	154
VLB 43c-5a	1.57	.027	.010	58	157
VLB 43c-5b	1.25	.026	.010	48	125
Rockport, Texas: San Antonio Bay and Offshore Samples					
S 57-A	1.82	.026	.010	70	182
0–5 cm					
S 91-A	1.00	.015	.0057	67	175
10–15 cm					
S 91-A	1.88	.024	.0093	78	202
20–35 cm					
S 133-A	1.62	.029	.011	56	147
12–16 cm					
GR 7 PB	.349	.0073	.0029	48	120
J 32-A	1.04	.017	.0068	61	153
J 35-A	1.39	.035	.014	40	99
J 36-A	1.66	.018	.0072	92	231
Composite Samples					
Austin Chalk	2.03	.020	.0079	102	257
Cherokee	1.32	.018	.0072	73	183
Eagle Ford Shale	.208	.0026	.0010	80	208
Lower Eutaw	1.40	.021	.008	67	175
Miocene Nodular	.938	.010	.0040	94	235
Selma Chalk	1.45	.018	.0072	81	201
Tuscaloosa sandstone	.930	.016	.0061	58	153

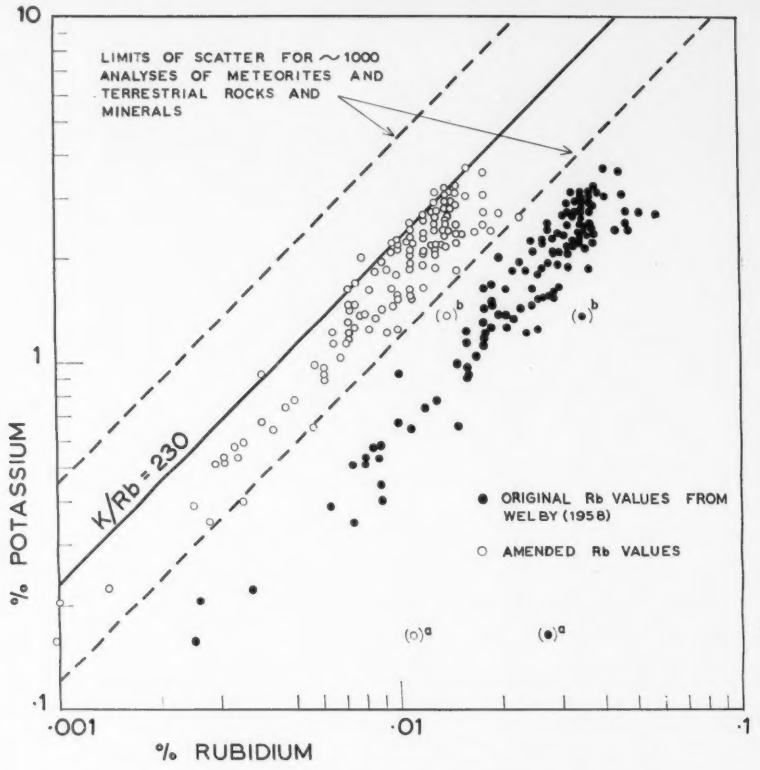

FIG. 1.—Plot of the original and the amended Rb values versus K.

In conclusion, the value of using such international interlaboratory standards as G-1 and W-1 which has been previously stated (see for example, Ahrens, 1957; Ahrens and Fleischer, 1960) is again stressed. Analytical data which have been obtained through the use of such standards can be amended as more accurate determinations of elements are made in the basic standards.

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ORIENTATION OF ORTHOCERACONE CEPHALOPODS AT LEMONT, ILLINOIS[1]

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Few studies have been published on orthoceracone cephalopod orientations in sedimentary rocks; probably one of the major reasons for this is the lack of exposures of wide horizontal extent with preserved specimens. Theoretical considerations indicate that open cones in moving water, will, in general, be oriented such that their apices will point toward the prevailing current source. Petránek and Komárková (1953) have shown that in the Silurian Budany Limestone, shells lay with their apices pointing toward the source of current which moved from south-southwest to north-northeast. The cephalopods of the Devonian Hlubocĕpy Limestone show less definite arrangement with two directions predominating at right angles to one another. Cross waves or low velocity currents are regarded as the explanation.

Kay (1945) found two straight cephalopod orientation maxima at right angles to each other at St. Joseph Island in Ontario, Canada, and at Cumberland Head, Vermont. Large shells were found at right angles to smaller ones at both places. Kay suggested that the large shells were oriented normal to the shoreline and the small ones parallel to it.

Ruedemann (1897) reported a parallel orientation of the rhabdosomes of graptolites, sponge spicules, fragments of bryozoans, and shells of straight cephalopods in the Utica Shale. The smaller ends of the cephalopods and often sicular ends of the graptolites pointed eastward, and drift lines of fossil fragments were found behind the apertures of large cephalopod shells. Ruede-

[1] Manuscript received August 31, 1959.

mann concluded that the prevailing currents came from east-northeast.

The present author studied orthoceracone cephalopod and crinoid orientations in a small, unnamed flagstone quarry half a mile north of Lemont, Illinois, between the Sanitary and Ship Canal and the Des Plaines River. The overlying soil had been stripped off and Middle Silurian Waukeshaw beds were exposed; the surface area of the quarry was about 400,000 square feet. The depth of excavation varied from approximately 1 ft to less than 4 ft; several beds were widely exposed. Lowenstam (1948) gives a detailed description of the lithology of these beds; it is sufficient to note that the beds are composed of a light gray dolomite which weathers buff upon exposure and contains a small amount of clay. The Waukeshaw here is quite fossiliferous. Corals, crinoids, bryozoans, calcareous algae, cephalopods, brachiopods and trilobites occur locally in abundance. Preservation is in the form of casts and molds; secondary silicification is quite prominent. About one year after exposure of several non-silicified orthoceracone cephalopods, considerable silicification had developed along septae.

Large numbers of orthoceracone cephalopods and a number of crinoid stems were scattered over the quarry; most of them were found on one bed which covered approximately half of the quarry floor. A number of small, elongated coffin-like structures, probably small reefs, were located at various spots on the quarry floor with an occasional cephalopod nearby. The reefs trended northeast-southwest, suggesting that the prevailing winds and currents may have come from one of these two directions; further evidence (Lowenstam, 1950, 1957) indicated that the prevailing direction had been from the southwest.

Orientation readings on 106 orthoceracone cephalopods were taken to determine whether their direction corresponded to the regional wind and current direction as determined by Lowenstam. All cephalopods measured were located on a single bed which covered approximately half of the exposed area. Orientations were taken with the Brunton compass, and the condition of each fossil was noted. Finally the orientation of each individual was plotted on a topographic map of the area for further study.

Figure 1 shows the orientation direction of all measured cephalopods. All orientation measurements over each 20° arc were placed in one class and figured on the chart; the orientation indicated is the midpoint of the class. There are clearly two trends, the major west-northwest one and a secondary south-southwest trend. Figure 1 includes cephalopods found near the small reefs; if these fossils are removed from the diagram, the 10 specimens facing the secondary peak (south-southwest) are reduced to six and this peak is eliminated. Orientations of a number of crinoid stems were also taken; the prevailing direction was west-northwest, east-southeast corresponding to cephalopod orientations.

Many specimens were not parallel to the bedding but dipped with apices down at small angles; these were more frequently preserved than apertural ends. If these organisms had been swept along by strong currents, the apices of some might have become embedded in the substratum, thereby being protected from mechanical erosion and solution effects. That there were strong currents is indicated by inverted colonial corals which must have been uprooted during periods of turbulence. In general the clay content is concentrated in lenses which

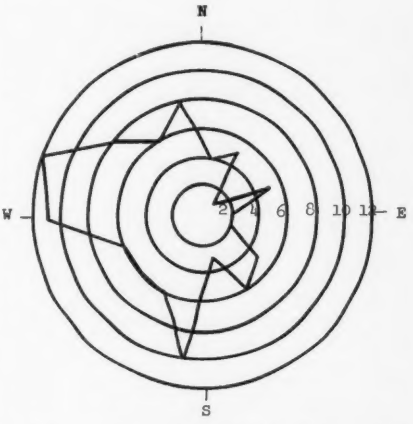

FIG. 1.—Orientation of 106 orthoceracone cephalopods on a single bed at Lemont, Illinois. Apices point in the indicated compass direction.

become thinner and more numerous from west to east. These lenses suggest periods of relative calm which probably alternated with episodes of current action such as those which oriented the cephalopods and uprooted corals. Crinoid calyxes and rootlets may have been covered and preserved immediately after cessation of current action; Lowenstam (1948) suggests that the small reefs died after heavy agitation stirred up bottom sediments which then settled and suffocated the organisms.

Four cephalopods and a large number of trilobites were noted close together in one section of the quarry on the bed mentioned above. Preservation was not good, and many of the trilobites were difficult to identify. As a rough estimate, at least 100 specimens of *Calymene celebra* Raymond were present here, and the number could have been considerably greater; no other species were present. Orientation and size determinations were taken on as many trilobites as possible to determine whether the assemblage had been carried in by currents or had been buried in place. Although *C. celebra* is somewhat oval in shape, the possibility existed that the specimens were oriented by currents. Orientations were random, but the trilobite size range was small, probably indicating that they had been swept in and sorted by currents.

The cephalopod orientations at the Lemont quarry indicate a wind and current direction from the west-northwest, a direction at variance with the normal southwest direction of Lowenstam (1957). It is possible that the orthoceracone cephalopods and crinoids studied here were oriented by one intensive storm at a slight angle to the average wind and current direction.

This study shows that it is possible to examine certain ecological measures over essentially "instants" in time. It may eventually be possible to combine a number of these studies and examine the paleocologic record over very brief stratigraphic intervals. It is hoped that in some instances the changes will indicate whether or not the sedimentation rate was continuous. For instance, in Simpson's (1953) discussion of Brinkmann's (1929) study of morphological rates in *Kosmoceras*, Simpson was dealing with changes in morphological rates of evolution in relation to sedimentation and was able to infer a good deal about variation in the sedimentation rate over the small stratigraphic interval studied. Given information on the variation of certain ecological measures over short periods of time, it might be possible to determine changes in the rate of sedimentation from the changing ecological conditions over brief stratigraphic intervals.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 30, NO. 2, PP. 324–341
FIGS. 1–6, JUNE, 1960

SOCIETY RECORDS AND ACTIVITIES

REPORTS AND MINUTES OF THE THIRTY-FOURTH ANNUAL MEETING OF THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

The thirty-fourth annual meeting of the Society of Economic Paleontologists and Mineralogists was held in the Rutland Room of Haddon Hall, Atlantic City, New Jersey, April 25–28, 1960, in conjunction with the annual meeting of The American Association of Petroleum Geologists.

The Society's program consisted of papers on The Paleontological and Mineralogical Evidence for Polar Wandering and Continental Drift; Paleontology and Stratigraphy; and Sedimentary Mineralogy and Petrology.

At a joint session on Tuesday morning, April 26, Samuel P. Ellison, Jr., President of the S.E.P.M., presented the following address:

THINKING PATTERNS FOR GEOLOGISTS

Mr. Chairman, fellow members of the Society of Economic Paleontologists and Mineralogists, fellow members of the American Association of Petroleum Geologists, ladies and gentlemen, I propose to contribute to this program by presenting my views on how a geologist thinks. We have the power to improve and sharpen our geological wits if we will only understand the potential of our own system of thinking. We have no hesitancy in applying and accepting systems-engineering in practical industrial problems. Why should we not also accept, without hesitation, system in our own geological thinking?

My interest in the subject of thinking patterns is natural because of my employment in geological education. However, I intensified my concern on this matter after listening to a speech by Dr. Harry H. Ransom, Provost and Vice-President of the Main University, The University of Texas, when he addressed his faculty as follows: "In an age pre-occupied with outer space, the area still most important to education is that which lies between the human ears."[1]

[1] Ransom, Harry H., Feb. 1958, "Editorial," The Texas Quarterly, vol. 1, no. 1, Preface page. University of Texas Press, Austin, Texas.

The well-being and future progress of the geological profession are directly dependent upon the efficiency, alertness, sharpness and quantity of productive thinking that will go on in the space between our geological human ears. Every ton of ore, every pound of energy from fossil fuels and every gallon of ground water to be consumed by civilization in the future must first be a geological thought before it is a reality.

Geological thinking differs greatly from the thinking in other scientific disciplines because geology is mainly an observational science. It is impossible to bring the whole earth into the laboratory for a controlled experiment. Geological time cannot be reproduced in the laboratory and the geological clock cannot be turned back except through human imagination. Deductions, analogies and inferences based on observed data that are still in the process of being gathered are the backbone of many geological concepts. When experiments are set up to solve geological problems, the geologist finds himself overwhelmed with a continuously increasing interplay of complex factors as new data pour into the scene. The greatest virtue of geological thinking is the development of a disciplined continuous effort to seek new data, additional factors and alternative explanations. This is the life blood of geological activity.

The well known steps of the Scientific Method are the basic frame of reference for geological thinking patterns. Geologists, like all scientists, assemble and organize observed and experimental facts, interpret these facts and develop working hypotheses. Geologists use deductive and inductive thinking, devise experiments and make additional observations to test hypotheses and finally try to develop general natural laws. I have selected the following four categories as representing examples of typical geological thought patterns:

1. Data assembly and organization, si-

multaneously from multiple and complex sources.
2. Three dimensional thinking.
3. Time and sequence thinking.
4. Awareness of alternative interpretations.

Obviously, data assembly and organization is the first step in any scientific endeavor but the emphasis in geology is on gathering and organizing the facts from many complex sources simultaneously. Three-dimensional thinking and time and sequence thinking are distinctly geological and are applicable in all phases of the scientific method. Awareness of alternative interpretations remains a cardinal operating practice thoughout all steps of the scientific method.

DATA ASSEMBLY AND ORGANIZATION

Geologists bring together clues about rocks, minerals, fossils, stratigraphy and structure from every part of the earth's crust. Answers are obtained only after sifting great quantities of data. Good judgement and training will guide the worker in deciding what fragments of information are important on specific problems. A common geological task is the assembly of information on handy memory devices such as maps, logs and cross-sections. To assure himself of a thorough approach to a problem the geologist develops a flexible check list of sources of data. He performs somewhat like an airline pilot, who methodically checklists himself at every take-off and landing. The geologist differs from the airline pilot, however, in that he may expand or contract his check list as time and the economics of the situation dictate. It is not proposed that a geologist become a slave to a check list by mixing up his geological batter in accordance to a standard cook-book recipe. Instead, the geologist, always aware of the vast volumes of available data, will pick and choose the sources of information to fit within the limits of his budget and deadlines for completion of his maps and reports. The emphasis is to avoid the typical one-tract thinking patterns that so many of us are willing to follow because the path is easy.

A simple example of data assembly and organization is employed commonly in the gathering of information on a single exploration bore-hole. A well log has very little value unless the location, elevation, depths to lithologic and paleontologic key beds, and depths, thicknesses and patterns of lithologic and paleontologic units are immediately available. A subsurface geologist would not be caught with his elevation or location missing. He could do nothing about the structural picture of the well without depths to key beds. To make the well information useful he assembles on the log all of this data. The log strip then serves to hold the facts ready to be woven into a broader geological picture with other logs.

A complete information center may be constructed on a single log strip by assembly of several different logs such as self-potential curves, electrical resistivity curves, gamma ray curves, neutron ray curves, drilling time charts, caliper curves, lithologic logs, paleontologic logs, scout ticket information and engineering data. Karl A. Mygdal, geologist for the Pure Oil Company,[2] called these composite or executive logs.

Similarly it is common practice to construct composite or executive maps by combining structural, stratigraphic, lithofacies, thickness, geophysical, lease and ownership information on one plat. The map serves as an information center, analogous to a data processing machine which feeds back at a glance the whole picture for geological use. Many of us have failed to convince our executives to undertake a proposed exploration program because we failed to include on our logs or maps some vital bit of information. A flexible check-list designed to include this information would have saved the day for the exploration proposal.

Modern practice in the petroleum business employs the simultaneous assembly system in preparing for decisions on lease purchases, drilling deals and exploration programs. Management must have before it data from scouts, geologists, geophysicists, engineers, land men, legal council, pipeline experts, refiners and marketers before a final decision is made firm. Coordination and integration are words used to describe

[2] Mygdal, Karl A., May, 1948, Assemblage logs—Aid to management Petroleum Engineer, vol. 19, no. 8, pp. 242, 244, 247.

this activity but the basic idea is to obtain as much information as possible from as many pertinent sources as possible so the whole picture may be viewed at once.

Surprising as it may be the very purposes of the Society of Economic Paleontologists and Mineralogists are to promote the simultaneous assembly system of thinking. In Article II of the constitution of this society I quote: "The object of the Society shall be to promote the science of stratigraphy through research in paleontology and sedimentary petrology, especially as these relate to development of knowledge of the geology of petroleum."

There are hundreds of members of this society diligently engaged in seeking new knowledge and interpretations about the meanings of fossils, their stratigraphic distribution and environments. Few of these workers give significant attention to how much good information is being supplied about stratigraphy and environments of sedimentary rocks from the microscopes of the sedimentary petrologists. Likewise the sedimentary petrologists ignore completely how much data and new interpretations are being contributed by paleontologists. The fossils are as much a part of the sedimentary rock as the mineral grains. The very texture and composition of some rocks are controlled by fossils. Therefore, fossils must not be ignored. We ought to look forward immediately to the time when data from these two disciplines will be assembled simultaneously to give a more complete coordinated geological picture.

THREE-DIMENSIONAL THINKING

Most geological thinking involves three-dimensions. We advise prospective geology majors to take and pass an aptitude test to see whether they are capable of solving three-dimensional problems. Geologists are all aware of the importance of using their imagination to understand the positions of structure and stratigraphy in space. However, most of the data and interpretations are reduced to two-dimensional logs, maps, cross-sections and photographs. These two-dimensional flat pieces of paper are handy because they can be folded and filed for the purposes of clearing desk tops and keeping offices neat and trim.

Throughout our studies of rocks and minerals we try to understand the three-dimensional aspects of crystal structure, rock bodies and earth structure. Then, paradoxically, as advanced students we concentrate on petrology by studying thin-sections which are essentially two-dimensional. Seldom do we insist on thin sections taken in more than one direction from a single rock specimen.

In our effort to understand the three-dimensional factors of geology we invariably exaggerate the vertical scale. The fallacy of vertical exaggeration was forcibly demonstrated by Karl F. Dallmus when he gave his concepts on the shapes and origins of the sedimentary basins of the world. He showed that the floors of many basins were never deeper than would be allowed by the subtended chords of the earth's curved surface. This meant that many of our basins were really not concave saucer shaped features at all but rather convex shaped features with the floors less convex than the curvature of the earth.[3]

Scale models, peg models, stereograms and stereophotographs are required tools in any geological activity. Even though mining geologists and field geologists work in a three-dimensional conceptual environment, we ought to look forward to the time when the subsurface geologist, structural geologist, paleontologist, and petrologist will be surrounded with all kinds of aids to give three-dimensions to his work.

TIME AND SEQUENCE THINKING

Geology is the only discipline that stresses the importance of time. Geological concepts of time represent unique contributions to scientific thinking. Placing of geological events in their proper time position and perspective in the interpretation of earth history represents the goal of much geological thinking. A geologist who examines a rock, mineral or fossil specimen immediately tries to reconstruct the long history behind the specimen. The history includes the date and conditions of formation, and date

[3] Dallmus, Karl F., 1958, Mechanics of basin evolution and its relation to the habitat of oil in the basin. In *Habitat of Oil*, Spec. Publ. Am. Assoc. Petroleum Geologists, pp. 883–931.

conditions of lithification, date and number of times the specimen has been deformed, altered, and weathered. The geologist will try to read into the history the total sequence of events that have given the final product. He will recognize that the most recent events may mask or destroy evidence of earlier events.

Reconstruction of the sequence of events that shaped the rocks and minerals applies equally effective to the fluids in the earth. Robert F. Walters has shown how a reconstruction of geological history will permit us to trace the sloshing of fluids first in one direction, then another direction, back and forth, up and down, through permeable zones in the subsurface.[4] The final resting place of the various fluids, gas, oil and water is directly the result of the sequence of geological events in the particular region.

Paleogeographic, paleogeologic, palinspastic and paleotectonic maps are excellent ways to depict restored geological conditions for a particular geological date. These tools are not employed widely enough. Peg models of restored geology ought also be employed so that we could visulize three-dimensional geology for a particular time. Such restored three-dimensional models with the time factor incorporated would in a sense be four-dimensional.

AWARENESS OF ALTERNATIVE INTERPRETATIONS

For the past sixty-three years geologists have employed T. C. Chamberlin's method of multiple working hypotheses for working out interpretations that would account for given sets of geological facts.[5] Several working hypotheses are set up to explain a given group of facts. A search is made for additional data to prove or disprove each working hypothesis and finally a single hypothesis or some compromise combination hypothesis may be formulated to satisfy all of the conditions. Geologists now go a step further and show that even after exhaustion of all possible sources of data there still may remain two or more explanations for a given set of facts.

Ordinary electrical logs offer a simple example of how there may be two or more possible explanations for a given combination of electrical log curves. Assume that the electrical log shows a strong negative (to the left) self-potential curve indicating good permeability. Opposite the zone of permeability both shallow and deep penetrating resistivity curves show high resistivity readings (to the right). If the geologist does not examine his thinking closely and if he has no other data other than the electrical log he might say this zone contains oil. However, the same curves could be obtained from fresh water, gas, a cavern filled with drilling mud, or very very deep mud invasion. The log interpreter must always admit these alternative possibilities exist until other data from other sources give him a better answer.

Recently I have had the pleasure of examining acetic acid residues abundant with conodonts from the two feet of type locality surface exposures of the Chappel (Mississippian) limestone of central Texas. The conodonts from the Chappel have been given a great deal of study by W. H. Hass[6] from the United States Geological Survey. The facts are simple in that the Chappel limestone contains conodonts that are reported elsewhere from Lower Ordovician, Middle Devonian, Upper Devonian, Lower Mississippian, and Middle Mississippian. We can set up the following possible alternative interpretations to explain the age of Chappel formation conodonts:

A. Chappel faunas are Lower Mississippian with stratigraphic admixtures from below and stratigraphic leaks from above.
B. Chappel faunas are Middle Mississippian with stratigraphic admixtures from below.
C. Chappel faunas are transition from Lower Mississippian to Middle Mississippian with stratigraphic admixtures from below.
D. Chappel faunas are transition from Upper Devonian to Lower Mississippian with new age ranges for the fossils that seem to be out of place.
E. Chappel faunas are Lower Mississippian

[4] Walters, Robert F., 1958, Differential entrapment of oil and gas in Arbuckle dolomite of central Kansas,. Am. Assoc. Petroleum Geologists Bull., vol. 42, pp. 2133–2173.

[5] Chamberlin, T. C., 1897, The method of multiple working hypotheses, Jour. Geol. v. 5, pp. 837–848.

[6] Hass, W. H., 1959, Conodonts from the Chappel Limestone of Texas. U. S. Geol. Surv. Prof. Paper 294J, pp. 365–397, pls. 46–50.

with new age ranges for all fossils that seem to be out of place.

F. Chappel faunas are Middle Mississippian with new age ranges for all fossils that seem to be out of place.

G. Chappel limestone is zoned so that the bottom seven inches contain Lower Mississippian faunas with an admixture from below, and the top fourteen inches contain Middle Mississippian fauna.

Which of these possible choices will ultimately be correct depends upon additional field data and more assembly of information. There will undoubtedly also be additional alternative explanations.

CONCLUSIONS

In conclusion, I firmly believe that the geological profession could be greatly improved if each one of us would accept two challenges: first, searchingly re-examine and re-organize our own systematic thinking patterns to see if we are getting the best use of the space between our ears; and second, if we believe that our data assembly method, three dimensional thinking, time and sequence thinking, and awareness of alternative interpretations are all so good, we must advertize this to the world. Let the people know that we have a top flight product to offer and that we are solid contributors to scientific thinking.

No amount of group effort on our part to "certify" geologists or to form a professional registration system will substitute for vigorous and firm *individual* efforts to improve our lot.

Also at the joint session on Tuesday morning, President Ellison presented an honorary membership award to A. I. Levorsen. The award consists of a certificate and the receipt of both of our *Journals* for life.

President Ellison presenting Honorary membership scroll to A. I. Levorsen.

Dr. Levorsen was born in Fergus Falls, Minnesota, on July 5, 1894. He graduated as a Mining Engineer from the University of Minnesota in 1917. After working in the Mid-Continent region for fifteen years in consulting capacities and as chief geologist for several oil companies, he shared in the discovery of the Fitts Pool in Southern Oklahoma in 1933. From 1945 until 1951, he was professor and dean of the School of Mineral Sciences at Stanford University. Dr. Levorsen's consulting work has included assignments in South America, Europe, India, Africa, and Australia. He is author of one of the most widely accepted petroleum texts used in our universities, that is, *Geology of Petroleum*. He is editor of many geological contributions, including several A.A.P.G. books.

Levorsen is past president of The American Association of Petroleum Geologists, the Geological Society of America, and the American Geological Institute. His awards and recognitions are many—he is the possessor of the coveted Sydney Powers Memorial Medal which is the highest award granted by the A.A.P.G.; an honorary doctorate has been conferred on him by several institutions; and he was elected to honorary membership in the A.A.P.G. in 1958. Dr. Levorsen has been an active member of the S.E.P.M. for over twenty years.

Dr. John A. Wilson was the recipient of the award for a "Best Paper at the Convention." A two-volume book, *Mammals of North America*, was presented to him at the joint session, for his paper, "Stratigraphic Concepts in Vertebrate Paleontology," which was given at the 33rd Annual Meeting of the Society in Dallas, Texas, in 1959. His paper was judged, by a committee of five, on content, organization, originality, and presentation.

Now a professor of geology at the University of Texas, John A. Wilson was born November 3, 1914, in Lawrence, Massachusetts. His formal education was acquired at the University of Michigan where he was

President Ellison presenting book to John A. Wilson for best paper at 1959 Dallas Convention.

granted a B.A. degree in 1937 and a Ph.D. degree in 1941. Prior to joining the staff at the University of Texas in 1946, Dr. Wilson spent 2 years with the United States Naval Reserve and several years at the University of Idaho School of Mines as a teacher and a research geologist.

Professor Wilson's general field of interest is vertebrate geology. He has chosen the two-volume book, *Mammals of North America*, for his award. Dr. Wilson has published extensively, several papers having been accepted for publication in the *Journal of Paleontology* and *Bulletin* of the A.A.P.G.

Dr. Wilson is a member of The American Association of Petroleum Geologists, Society of Economic Paleontologists and Mineralogists, Paleontological Society, Geological Society of America, and American Association for the Advancement of Science. He has participated in National Science Foundation High School Teacher training programs and High School Science enrichment programs. The American Philosophical Society awarded him a travel grant for study in Europe during the summer of 1958. He was recognized for outstanding teaching service to The University of Texas on Honors Day in March, 1953.

In addition to the above awards, Research Committee Chairman, Arthur C. Munyan, presented the Society's Award for the Best Paper for 1958 in the *Journal of Paleontology* to Mrs. Christina Lochman-Balk and James Lee Wilson, for their paper entitled, "Cambrian Biostratigraphy in North America," published in the March issue, Volume 32, Number 2. (Mrs. Balk was unable to be present and Dr. Wilson received her certificate for her.) Dr. Munyan also presented the award for the Best Paper for 1958 in the *Journal of Sedimentary Petrology* to Louis I. Briggs, for his paper entitled, "Evaporite Facies," published in the March issue, Volume 28, Number 1.

The Best Paper Awards are the sixth to be presented by the S.E.P.M. They consist of a certificate given to the author whose paper, appearing during the second preceding year, is judged by the Research Committee to be the most outstanding contribution of the year.

Born in Springfield, Illinois, on October 8, 1907, Mrs. Balk graduated from the Springfield High School in 1925 and in 1929 received a B.A. degree from Smith College (summa cum laude). After obtaining a M.A. degree from the same institution, she did graduate work at Johns Hopkins University

CHRISTINA LOCHMAN-BALK
Co-author of Best Paper in 1958
Journal of Paleontology

receiving her Ph.D. degree in 1933. In 1934, Mrs. Balk was the recipient of a National Research Council grant for study of the Cambrian of Llano District, Texas. In 1959 she was awarded a National Science Foundation grant to describe the Upper Cambrian Faunas of the Deadwood formation, South Dakota.

From 1935 until 1947 Dr. Balk taught geology at Mount Holyoke College, advancing from instructor to associate professor. She has lectured in geology both at the University of Chicago and Johns Hopkins University. From 1955 until 1957, Mrs. Balk was stratigraphic geologist with the New Mexico Bureau of Mines and since 1957 has been a professor of geology at New Mexico Institute of Mining and Technology, Socorro, New Mexico.

In addition to her membership in the S.E.P.M., Dr. Balk is a member of Sigma Xi, American Association for the Advancement of Science, Paleontological Society, Geological Society of America, and New Mexico Geological Society.

Mrs. Balk was honored by the Society at its Annual Meeting in Los Angeles in 1958 for the best paper appearing in the 1956 *Journal of Paleontology*. The subject for this award was, "The Evolution of Some Upper Cambrian and Lower Ordovician Trilobite Families." published in Volume 30, Number 3.

President Ellison presenting certificate to James Lee Wilson for Best Paper in 1958 *Journal of Paleontology*, co-authored with Christina Lochman-Balk.

President Ellison presenting certificate to Louis I. Briggs for Best Paper in 1958 *Journal of Sedimentary Petrology*.

James Lee Wilson was born in Waxahachie, Texas, December 1, 1920. He attended the University of Texas where he received B.A. and M.A. degrees in 1942 and 1944. Yale University granted him a Doctor of Philosophy degree in 1949.

Dr Wilson was employed for 1 year by the Carter Oil Company as a field geologist, but upon graduation from Yale, he accepted a position with the University of Texas, teaching paleontology, stratigraphy, and field geology. Wilson left the University in 1952 to join Shell Development as a research geologist.

Mr Wilson's fields of interest are carbonate geology and Cambrian paleontology and stratigraphy. In addition to articles in the *Journal of Paleontology*, he has published, among others, in the *Bulletin* of The American Association of Petroleum Geologists and in the *American Journal of Science*.

In addition to S.E.P.M. membership, Dr. Wilson is a member of The American Association of Petroleum Geologists and the Paleontological Society. He is a fellow of the Geological Society of America and is currently serving on the S.E.P.M. Publications Committee.

Louis I. Briggs was born April 24, 1921, in Los Angeles, California. He attended

Fresno State College and received his Bachelor of Arts degree from that institution in 1943. He then continued his graduate work at the University of California at Berkeley from 1946–1950, receiving his Doctor of Philosophy degree in 1950.

From 1946–1950 Professor Briggs held the appointment of teaching assistant in geological sciences at the University of California. He had served in the U. S. Navy as a lieutenant in the Pacific Theatre from 1943 until 1946.

Dr. Briggs first came to The University of Michigan as an instructor in geology in 1950. Since coming to the University he has served as a concentration advisor for geology and as a counselor for the Unified Science Program. He presently has charge of the Subsurface Laboratory and Core Library.

Professor Briggs has published many articles on sedimentary petrology in the *G.S.A. Bulletin, Journal of Sedimentary Petrology, American Mineralogist, California Division of Mines Bulletin,* and others. He is a member of the Geological Society of America, American Association of Petroleum Geologists, American Geophysical Union, Association of Geology Teachers, and the Geochemical Society of America. He has been a member of the S.E.P.M. since 1951.

ANNUAL BUSINESS MEETING

The annual business session of the Society was called to order at 1:30 P.M., Tuesday, April 26, by Samuel P. Ellison, President, who introduced the officers for the new year as follows: President, William M. Furnish; Vice-President, Laurence L. Sloss; Secretary-Treasurer, John Imbrie; Editors of the *Journal of Paleontology*, M. L. Thompson and Charles W. Collinson; and Editor of the *Journal of Sedimentary Petrology*, Jack L. Hough.

It was moved, seconded, and carried that the minutes of the 1959 meeting be approved as published in the June, 1959, *Journal of Sedimentary Petrology* and the July, 1959 *Journal of Paleontology.*

The following reports were not presented at the Business Meeting, but instead they are printed in full below.

OUTGOING AND INCOMING SEPM COUNCIL

First Row—left to right: Gordon Rittenhouse, outgoing Past-President; Samuel P. Ellison, outgoing President; William M. Furnish, incoming President; Back Row, Left to right: John Imbrie, Secretary-Treasurer; L. L. Sloss, incoming Vice-President; William J. Plumley, outgoing Vice-President; Jack L. Hough, Editor of the *Journal of Sedimentary Petrology*; M. L. Thompson, Co-Editor of the *Journal of Paleontology*. Not shown in picture—Charles W. Collinson, Co-Editor of *Journal of Paleontology.*

1. *Report of the Editors of the Journal of Paleontology (M. L. Thompson and Charles Collinson).*—Volume 33 of the *Journal of Paleontology*, issued in conjunction with the Paleontological Society, contains 1139 pages of text and 133 numbered plates of fossil illustrations. The Society of Economic Paleontologists and Mineralogists' portion of the volume contains 528 pages of text and 53 plates of fossil illustrations, which represents an increase of 110 pages of text and 14 plates of fossil illustrations over that of the preceding year. Contributions cover a broad field of interest about like the preceding volume.

Fossils representing practically every major phylum of animals and some plants are discussed in this volume, including protozoans, sponges, molluscans, corals, brachiopods, bryozoans, graptolites, starfish, eurypterids, algae, rodents, and several groups of fossils of undetermined origins. One paper deals with a general fauna. Others concern ecology, invertebrate anatomy, and paleontologic techniques.

Contributions include thirty-two papers, fifteen paleontologic notes, and four reviews. Eleven papers concern larger types of fossil specimens, and eighteen concern what may be classified as microfossils. A stratigraphic summary of the thirty-two papers indicates that eighteen are of fossils of Paleozoic age, two are of fossils of Mesozoic age, and ten are of fossils of Cenozoic age. The others cannot be classified as to geologic age.

The number of contributions presented to the Journal of Paleontology for consideration has increased considerably during the past year. Unpublished manuscripts on hand are about half again greater than at this time last year.

The Illinois Geological Survey furnished secretarial, technical, and financial assistance.

2. *Report of the Editor of the Journal of Sedimentary Petrology (Jack L. Hough).*—*The Journal of Sedimentary Petrology* was published in 1959 as Volume 29, Numbers 1 through 4. The size of the Journal was again increased, this time from 148 pages per number to 160 pages per number, beginning with the June issue. A summary of the contents is given in the accompanying table. Despite the increase in size of the Journal, the supply of manuscripts awaiting publication has continued to increase during the year, so that there is again a delay in publication of 10 or 11 months for manuscripts currently received.

The national origins of the articles, notes, and discussions of Volume 29 were as follows:

United States	51
England and Wales	7
Canada	3
Australia	3
India	2
New Zealand	1
Japan	1
Denmark	1
Norway	1

Dr. Frederick W. Cropp, of the University of Illinois staff, was appointed Managing Editor in September, to assist with the increased work of editing the Journal.

As in the past ten years, the University of Illinois has provided the services of the Editor and of a part-time student editorial assistant.

3. *Report of the Secretary-Treasurer (John Imbrie).*—Net income for the year ended December 31, 1959, was $3,868. This com-

Journal of Sedimentary Petrology, Vol. 29, 1959

	Articles		Notes		Discussions		Reviews		S.E.P.M. Data[1] Pages	Advertising[2] Pages	Other[3] Pages	Total Pages
	No.	Pages	No.	Pages	No.	Pages	No.	Pages				
1. (Mar.)	13	111	1	2	1	1	2	3	21	2	8	148
2. (June)	16	128	3	6	—	—	1	1	21	3	5	164
3. (Sept.)	17	147	3	6	—	—	—	—	—	1	6	160
4. (Dec.)	13	142	2	3	—	—	—	—	—	2	13	160
Total	59	528	9	17	1	1	3	4	42	8	32	632

[1] Including membership list (March) and minutes of Annual Meeting (June).
[2] Exclusive of advertisements on covers.
[3] "Other" includes title pages, index, errata, and miscellaneous announcements.

pares with $5,883 for the preceding year, a drop of $2,015. This drop reflects the fact that, while our total income (including dues, subscriptions, sales of special publications and back numbers, and income from other sources) has increased $6,993, our total costs and expenses have increased $9,008. Disregarding inventory changes, the total increase in expenses to be accounted for is $8,025. Of this amount, $3,426 is due to the difference between the cost of printing *Silica in Sediments* and the cost of printing the *Journal of Sedimentary Petrology Index* the previous year. The balance is due to an increase in printing costs for the two journals ($3,302) and to an increase in administrative expenses ($1,297), chiefly salaries (up almost $500) and postage (up almost $400).

Only one special publication is operating at a financial loss, the *Journal of Sedimentary Petrology Index. Silica in Sediments* paid for itself in only nine months, and is now in the profit column.

To summarize the financial side of the picture, it is clear that the position of the Society remains a strong one. In particular, we may feel satisfaction from the fact that this position has been maintained in the face of rising costs. The success of our financial operations can be attributed, first, to the fact that the Society, through its publication program and in other ways, continues to serve the profession and to play a unique and valuable role; and, second, to the skill and imagination exercised by our headquarters staff and by our editors.

As regards membership, the Society continues to show a modest but progressive increase. As of December 31, 1959, our rolls include a total of 1530 members, including 1134 active members, 384 associates, 6 correspondents, and 6 honorary members. This total reflects a net gain of 74 over the previous year. Viewed as a percentage increase (0.5%) this growth rate is essentially the same as the Society has maintained since 1956. It is interesting to note that A.A.P.G. membership figures show about the same rate of increase for this period, and that the percentage of A.A.P.G. members belonging to S.E.P.M. has remained steady

(*Continued on page 336*)

MEMBERSHIP, MAILING, AND JOURNAL STATISTICS

	Dec. 31, 1959	*Dec. 31, 1958*	*Dec. 31, 1957*
1. S.E.P.M. Membership:			
Active Members	1134	1094	1085
Associates	384	351	319
Correspondents	6	6	6
Honorary Members	6	5	3
	1530	1456	1413
2. *Journal of Paleontology* Mailing List:			
S.E.P.M. Active & Honorary Members	509	503	528
S.E.P.M. Associates	173	167	160
Subscribers	962	912	840
P.S. Members	699	649	638
	2343	2231	2166
3. *Journal of Sedimentary Petrology* Mailing List:			
S.E.P.M. Active & Honorary Members	775	726	721
S.E.P.M. Associates	261	220	207
S.E.P.M. Correspondents	6	6	6
S.E.P.M. Subscribers	1076	997	979
	2118	1949	1913
4. Edition of *Journal of Paleontology*	2500	2500	2400
5. Edition of *Journal of Sedimentary Petrology*	2600	2500	2400
6. Number of pages, *Journal of Paleontology*	1139	1170	1190
7. Number of plates, *Journal of Paleontology*	133	148	150
8. Number of pages, *Journal of Sedimentary Petrology*	632	528	484
9. New Members	153	125	150
10. Transfers to active membership	32	24	49
11. Members and associates dropped for non-payment of dues (1/1/60).	43	65	49

REPORT OF CERTIFIED PUBLIC ACCOUNTANTS

The Council, Society of Economic Paleontologists and Mineralogists:

We have examined the accompanying balance sheet of the Society of Economic Paleontologists and Mineralogists at December 31, 1959, and the related statement of income and surplus for the year then ended. Our examination was made in accordance with generally accepted auditing standards, and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

In our opinion, the statements mentioned above present fairly the financial position of the Society of Economic Paleontologists and Mineralogists at December 31, 1959, and the results of its operations for the year then ended, in conformity with generally accepted accounting principles applied on a basis consistent with that of the preceding year.

ARTHUR YOUNG & COMPANY

Tulsa, Oklahoma, January 18, 1960

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
BALANCE SHEET, DECEMBER 31, 1959

ASSETS

	Total	*General Fund*	*Publication Fund*
CURRENT ASSETS:			
Cash	$40,763.71	$31,220.83	$ 9,542.88
Savings account	3,919.64	3,919.64	—
Accounts receivable	442.52	359.52	83.00
Total current assets	$45,125.87	$35,499.99	$ 9,625.88
PUBLICATIONS:			
Journal of Paleontology:			
Issues prior to 1959—10,078 journals at $0.50 each (1,541 complete volumes)	$ 5,039.00	$ 5,039.00	$ —
Issues 1 to 6 of 1959—773 journals, at cost	1,523.36	1,523.36	—
Reprints in 1948, Volume 1, 1927—633 volumes, at cost	1,375.39	1,375.39	—
Journal of Sedimentary Petrology:			
Issues prior to 1959—5,300 journals at $0.50 each (1,405 complete volumes)	2,650.00	2,650.00	—
Issues 1 to 4 of 1959—1,480 journals, at cost	1,870.83	1,870.83	—
Special publications, at cost:			
Turbidity Currents, 31 copies	26.51	—	26.51
Recent Marine Sediments, 246 copies	507.62	—	507.62
Finding Ancient Shorelines, 21 copies	36.70	—	36.70
Regional Aspects of Carbonate Deposition, 86 copies	191.99	—	191.99
Journal of Sedimentary Petrology Index, 1,312 copies	757.42	—	757.42
Silica in Sediments, 993 copies	2,192.54	—	2,192.54
Total publications	$16,171.36	$12,458.58	$ 3,712.78
FURNITURE AND FIXTURES (less reserve, $1,793.84)	$ 1.00	$ 1.00	$ —
DEFERRED CHARGES	$ 2,864.84	$ 2,168.84	$ 696.00
	$64,163.07	$50,128.41	$14,034.66

LIABILITIES AND SURPLUS

CURRENT LIABILITIES:			
Accounts payable	$ 4,382.08	$ 4,377.08	$ 5.00
Amount payable to Paleontological Society	4,086.02	4,086.02	—
Total current liabilities	$ 8,468.10	$ 8,463.10	$ 5.00
DEFERRED CREDITS:			
Subscriptions to journals—net of portion to be received by Paleontological Society	$12,203.35	$12,203.35	$ —
Membership dues for 1960	$10,286.00	$10,286.00	$ —
Total deferred credits	$22,489.35	$22,489.35	$ —
SURPLUS	$33,205.62	$19,175.96	$14,029.66
	$64,163.07	$50,128.41	$14,034.66

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
STATEMENT OF INCOME AND SURPLUS
YEAR ENDED DECEMBER 31, 1959

	Total	General Fund	Publication Fund
INCOME:			
Membership dues and subscriptions:			
Journals of Paleontology and Sedimentary Petrology	$ 4,947.00	$ 4,947.00	$ —
Journal of Paleontology	17,600.02	17,600.02	—
Journal of Sedimentary Petrology	14,471.44	14,471.44	—
	$37,018.46	$37,018.46	$ —
Sales of special publications:			
Turbidity Currents	$ 197.25	$ —	$ 197.25
Recent Marine Sediments	998.00	—	998.00
Finding Ancient Shorelines	148.90	—	148.90
Regional Aspects of Carbonate Deposition	891.50	—	891.50
Journal of Sedimentary Petrology Index	242.00	—	242.00
Silica in Sediments	4,629.00	—	4,629.00
	$ 7,106.65	$ —	$ 7,106.65
Sales of back numbers:			
Journal of Paleontology	$ 4,579.35	$ 4,579.35	$ —
Journal of Sedimentary Petrology	1,517.95	1,517.95	—
	$ 6,097.30	$ 6,097.30	$ —
Sales of plates	$ 569.30	$ 569.30	$ —
Advertising	$ 433.20	$ 433.20	$ —
Donation from The American Association of Petroleum Geologists	$ 2,040.00	$ 2,040.00	$ —
Miscellaneous	$ 429.36	$ 429.36	$ —
	$53,694.27	$46,587.62	$ 7,106.65
Less portion of 1959 income accrued to Paleontological Society	$ 3,270.22	$ 3,270.22	$ —
INCOME	$50,424.05	$43,317.40	$ 7,106.65
COSTS AND EXPENSES:			
Cost of printing:			
Journal of Paleontology	$13,681.56	$13,681.56	$ —
Journal of Sedimentary Petrology	12,187.36	12,187.36	—
Silica in Sediments	4,605.89	—	4,605.89
	$30,474.81	$25,868.92	$ 4,605.89
Expenses:			
Clerical salaries	$ 8,235.00	$ 8,235.00	$ —
Office supplies	501.81	501.81	—
Postage and express	1,992.55	1,992.55	—
Office rent	2,000.00	2,000.00	—
Telephone	72.16	72.16	—
Audit fee	215.74	215.74	—
Payroll taxes	197.84	197.84	—
Miscellaneous	2,361.80	2,050.55	311.25
	$15,576.90	$15,265.65	$ 311.25
Adjustment for (increase) decrease in inventory of publications	$ 504.21	$ 1,424.39	$ (920.18)
	$46,555.92	$42,558.96	$ 3,996.96
NET INCOME	$ 3,868.13	$ 758.44	$ 3,109.69
SURPLUS AT DECEMBER 31, 1958	29,337.49	18,417.52	10,919.97
SURPLUS AT DECEMBER 31, 1959	$33,205.62	$19,175.96	$14,029.66

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
NOTE TO FINANCIAL STATEMENTS
DECEMBER 31, 1959

It is the opinion of counsel that the Society, as a division of The American Association of Petroleum Geologists, is exempt from federal income tax under provisions of Section 501(c) of the Internal Revenue Code, except to the extent of "unrelated business income." The Society, based on the opinion of counsel, has taken the position that none of its income is "unrelated business income" within the provisions of Section 512 of the Internal Revenue Code and therefore no liability has been provided for federal and state income taxes in the financial statements.

(*Continued from page 333*)

at about 7.5. This is somewhat surprising in view of the increased attention paid in recent years to the field of research represented by our Society.

It is with sincere regret that we report the death of the following members during 1959:

Francesco Cipolla
Alexander Deussen
Charles R. Fettke
W. D. Kleinpell
Walter C. Toepelman

4. *Report of the Research Committee* (*Arthur C. Munyan, Chairman*).—Membership of this Committee is:

1960	*1961*	*1962*
H. A. Ireland	Heinz Lowenstam	Eduardo Guzman
Grover E. Murray	W. H. Akers	R. H. Schweers
W. D. Pye	Phil W. Reinhart	M. L. Natland
L. M. Cline	F. B. Van Houten	H. N. Frenzel
S. G. Wissler	A. C. Munyan	R. N. Ginsburg

The Committee, at its annual meeting in Los Angeles on March 10, 1958, selected the topic "Paleontological and Mineralogical Aspects of Polar Wandering and Continental Drift" for a symposium to be presented in 1960 at Atlantic City. Co-chairmen W. C. Gussow and Gordon Rittenhouse contributed much time and effort to selecting speakers and to moderating the symposium sessions. The completed program was as follows:

Session I

Presiding:
Arthur C. Munyan, Chairman of Research Committee.
Wm. C. Gussow, Union Oil Company, Calgary, Alberta.

S. W. Carey (University of Tasmania, Hobart, Tasmania) Tectonic Approach to the Problem of the Dispersion of the Continents.
Warren Hamilton (U. S. Geological Survey, Denver, Colorado) Antarctic Tectonics and Continental Drift.
H. J. Harrington (Tennessee Gas Transmission Co., Houston, Texas), Deep Focus Earthquakes in South America and their Possible Relation to Continental Drift.
S. K. Runcorn (King's College, Newcastle Upon Tyne, 1, England), Paleomagnetism and Relative Movements of the Poles and Continents.
B. W. Wilson (Shell Development Company, Houston, Texas), Measurement of Rock Magnetism in Sandstone Samples.
E. R. Deutsch (Imperial Oil Limited, Calgary, Alberta), Polar Wandering and Continental Drift: An Evaluation of Recent Evidence.
B. C. Heezen (Lamont Geological Observatory, Palisades, New York), Deep Sea Topography.
G. W. Bain (Amherst College, Amherst, Massachusetts), Climatic Zoning During the Geologic Past.

Session II

Presiding:
Gordon Rittenhouse, Shell Development Company, Houston, Texas.
Arthur C. Munyan, Chairman Research Committee.

Ting Ying H. Ma (Taipei, Taiwan), Continental Drift and the Sudden Displacement of the Solid Earth over the Liquid Core.
K. E. Caster (University of Cincinnati, Cincinnati, Ohio), The Meaning of Austral Siluro-Devonian Realms.
S. C. Nordeng (Michigan College of Mining and Technology, Houghton, Michigan), Pre-cambrian Stromatolites as Indicators of Polar Shift.
A. G. Fischer (Princeton University, Princeton, New Jersey) Distribution and Growth Patterns of Silurian Tabulate Corals Compared to Three Paleogeographic Hypotheses.
Maurice Ewing (Lamont Geological Observatory, Palisades, New York), Theories of Glaciation and Ice Age Formation.
Wm. C. Gussow (Union Oil Co. of California, Calgary, Alberta), Metastasy.
C. R. Longwell (c/o U.S.G.S., Menlo Park, California), General Comments on the Problems of Polar Wandering and Continental Drift.

The Committee, polled during 1959 to nominate an Honorary Member, overwhelmingly recommended A. I. Levorsen to the council for election. President Ellison notified Dr. Levorsen of his election by council.

Another poll of the Committee resulted in selection of two possible Correspondents, but council action was deferred because of time. The names will be referred to the incoming committee for future action.

The best paper in the *Journal of Sedimentary Petrology* for 1958, selected by the Committee, was determined to be that by Louis I. Briggs entitled *Evaporite Facies*, March, 1958. The best paper in the *Journal of Paleontology* for 1958 was chosen as that by Christina Lochman Balk and James Lee Wilson entitled *Cambrian Biostratigraphy in North America*, March, 1958. The awards for these papers were presented to the authors at the annual meeting in Atlantic City.

5. *Report of the Publications Committee (H. A. Ireland, Chairman).*—The Publications Committee of the S.E.P.M. is composed of H. A. Ireland, Chairman, J. L. Wilson, C. L. Cooper, Tjeerd van Andel, and A. C. Munyan as Chairman of the Research Committee. Terms of the first two named, continue into 1961 and the other three expire in 1960. The new Chairman of the Research Committee automatically becomes a member.

The principal action taken by the Committee was on the publication of the symposium on Concepts of Stratigraphic Classification and Correlation presented at the Dallas meeting in March, 1959. After much discussion at the Dallas meeting and subsequent correspondence it was decided not to recommend publication of the symposium and a report of the reasons was made to the Council for final consideration and action.

A paper by M. S. Rosenfeld and J. L. Fitch on Rapid Chemical Analysis of Sedimentary Rocks was submitted by the President for examination as a possible special publication. The paper was excellent, but it was decided that there would be insufficient demand to justify the cost of publication. It was recommended as a publication for the *Journal of Sedimentary Petrology* with a condensation of the tables and other appended matter.

An agreement was recommended and passed by the Council to extend purchase of S.E.P.M. publications at member prices to all members of the Geological Society of America and that the G.S.A. would extend similar price reductions of their publications to members of the S.E.P.M. R. C. Moore, President of the Geological Society of America, was notified of the action for their approval.

6. *Report on the Earth Sciences Division of the National Research Council (John C. Frye, S.E.P.M. Representative.)*—The Division of Earth Sciences, in keeping with its primary objective, rendered service to federal agencies and technical and scientific groups. These services were rendered through twelve advisory committees ranging from Arctic Sea ice to atomic waste disposal, and five technical committees. The technical committees include AMSOC (feasibility of drilling through the crust of the earth), Clay Minerals, Glacial Map of the United States East of the Rockies, National Atlas of the United States, and Topographic Maps Illustrating Cultural Geography. In addition, the American Geological Institute and the Advisory Board on education operate through the facilities of the Academy-Council.

The annual meeting of the Division was held on March 20, 1959, during the joint annual meeting of the Research Council. and was attended by the S.E.P.M. representative. This was the second year in which all divisions met simultaneously in Washington with opportunity for general sessions of the entire Council. Topics discussed at the general sessions of the Council included: "The nature and conduct of fellowship programs in science," "U. S. science in foreign aid," "Means and patterns for the support of scientific research," and others.

At the annual meeting of the Earth Sciences Division the following items, published during the year as a result of divisional activities, were presented.

Thermal Considerations in Deep Disposal of Radioactive Wastes, by Francis Birch, NAS-NRC Pub. 588, July 1958

Annual Report of the Division of Geology and Geography, 1946–1947 (October 1958)

Annual Report of the Division of Earth Sciences, 1957–1958, (October 1958)

A Regional Geography of Iceland, by Vincent H. Malmstrom, NAS-NRC Pub. 584, April 1958

The Political Geography of Burgenland by Andrew F. Burghardt, NAS-NRC Pub. 587, June 1958

Indigenous Tropical Agriculture in Central America, by Craig L. Dozier, NAS-NRC Pub. 594, October 1958

Geography of Food Supply in Central Minas Gerais, by Kempton E. Webb, NAS-NRC Pub. 642, January 1959.

Physical and Chemical Properties of Sea Water, Proceedings of a conference held at Easton, Md., September 4–5, 1958, NAS-NRC Pub. 600, March 1959.

Oceanography 1960–1970, Chapter I: Introduction and Summary of Recommendations, by Committee on Oceanography, March 1959

Clays and Clay Minerals, Proceedings of the Fifth National Conference. held at Urbana, Ill., October 8–10, 1956, NAS-NRC Pub. 566, 1958

Guidebook for field excursion to northeastern Maryland and northern Delaware, Seventh National Conference on Clay Minerals, Washington, D. C., October 20–23, 1958.

Preliminary steps were taken toward the organization of a joint committee by the Divisions of Earth Sciences and Anthropology to deal with representation at the

International Congress of Quaternary Research to be held in Poland during 1961, and a possible invitation to the Congress to meet in the United States during 1965.

The Committee on the Glacial Map of the United States East of the Rockies completed its work during the previous year, and the resulting map was published by the Geological Society of America. The Committee on Clay Minerals held its eighth annual conference at the University of Oklahoma in October, 1959, and the 1960 meeting is scheduled for Purdue University, Lafayette, Indiana. The Advisory Screening Committee on Fulbright Awards for Geology was active during the year and a proposal has been made to the Organizing Committee of the XXI International Geological Congress that there be a session devoted to describing the various exchange programs.

The annual conference sponsored by the Division of Earth Sciences, held in Washington, D. C., on May 2, 1959, was attended by the S.E.P.M. representative. The subject for informal discussion was the Atomic Energy Commission's "Project Plowshare" which is concerned with the non-military uses of nuclear explosives.

7. *Report on the American Geological Institute* (*Gordon Rittenhouse*).—Your senior representative attended the AGI Board of Directors meeting in Dallas, but was unable to attend in Pittsburgh. As reported last year, AGI finances are a critical problem, and have led to the appointment of a committee, B. W. Beebe, chairman, to consider reorganization of AGI. This committee has been extremely active and is expected to submit proposals for reorganization at the time of the AAPG-SEPM meeting in Atlantic City. The problems facing AGI and the need for a new look at the future of this organization were presented by President R. C. Moore, in the January-February, 1960 issue of "GeoTimes."

8. *Report of the S. E. P. M. Representative to the A.G.I. Government Relations Committee* (*Norman S. Hinchey*).—The A.G.I. Government Relations Committee met on March 31 and November 2, 1959. Among matters considered were: the need for a government relations committee, the membership of the committee, a program of responsibilities of the committee and a current study of government influences on the earth sciences. It was recommended that the Executive Committee of A.G.I. participate, with the Chairman of the G. R. Committee and the Executive Director of A.G.I., in implementing the attempt of the G. R. Committee to provide leadership and direction of that committee's efforts.

9. *Report of the Permian Basin Section* (*Carl Ulvog*).—The fifth annual meeting of our section is being planned for April 14, 1960, at Abilene, Texas. Registration is scheduled to begin the afternoon of April 13th at meeting headquarters, The Windsor Hotel. Mr. James K. Munn of Pan American Petroleum Corporation is general chairman and Dr. John P. Brand of Texas Technological College is in charge of the one-day technical program.

A field conference on the central part of the Bend Arch will follow the technical program and business meeting, being slated for April 15 and 16. Registration for the field trip will be accepted on April 13 and 15 at meeting headquarters in Abilene. Mr. Thomas Hambleton of Texaco is general chairman of the field meet. Exposures of lower Permian and Pennsylvanian rocks will be studied under the general leadership of Mr. Leonard F. Brown of the Bureau of Economic Geology.

Officers elected for the 1959-1960 term are: Carl Ulvog, President; Thomas Hambleton, 1st Vice-President; John P. Brand, 2nd Vice-President; Raymond W. Rall, Secretary; and Charles A. Reinke, Treasurer. Voting for the 1960-1961 officers will not be concluded until March 1, 1960; thus the new executive committee cannot be named at this writing.

Membership in our Section now totals 202, of which 190 reside in the Permian Basin area.

10. *Report of the Gulf Coast Section* (*David E. Pope*).—Under the leadership of President Marcus A. Hanna, the Gulf Coast Section was very active during the past year, 1958–59, in the ventures enumerated below.

On May 2, 1959, a field trip was conducted jointly with the Houston Geological Society. This trip, "Lower Tertiary and Upper Cretaceous of Brazos River Valley, Texas," continued the study of the central Texas Brazos River section, the upper portion of which was covered by the December

6, 1958, field trip of the Gulf Coast Section and the Houston Geological Society. The field trip committee again consisted of E.H. Rainwater, chairman, C. W. Stuckey, Jr., H. G. Schoenike, H. B. Stenzel, and L. J. Vittrup; and, Fred E. Smith, Professor of Geology at Texas A. & M. College, was again the field trip leader. He, assisted by several others, compiled an excellent guidebook for the trip. C. W. Stuckey, Jr. and E. H. Rainwater also joined in describing the geologic section and history of the localities visited. Marcus A. Hanna contributed by studying the outcrops and explaining the probable origin of the sedimentation and structural features exposed. Many other individuals assisted with this 90-odd mile trip, which was attended by more than 150 geologists.

The annual meeting of the Section was held in Houston, Texas, November 11–13, in co-operation with the Gulf Coast Association of Geological Societies. This convention was designated as the 1959 fall regional meeting of the American Association of Petroleum Geologists. Several members of the Section contributed to the program, especially to the portion of it devoted to the symposium for the field trip which followed the convention. Several members also acted as presiding co-chairmen for some of the technical sessions. These included Olin G. Bell and M. A. Hanna who served in this capacity for the opening session. The former was general chairman of the convention committees.

The annual business meeting was held November 12 after the technical sessions of that day. President Hanna asked for reports from the officers and committee chairmen; and, several projects of the section were discussed. The President thanked his officers, editor, and members for their co-operation during the year, and introduced the newly elected officers. The incoming president made a few brief remarks after which the meeting was adjourned.

"Recent Sediments of the North-Central Gulf Coastal Plain" was the subject of investigation for the field trip of November 14 and 15, 1959. This trip was routed along the coastal area from the western tip of Galveston Island, Texas, eastward to the vicinity of Creole, Louisiana. It was an extension of the field trip of October 30–November 1, 1958, "Sedimentology of South Texas," and was conducted jointly with the Gulf Coast Association of Geological Societies. The field trip committee consisted of H. R. Gould, chairman, H. A. Bernard, Marcus A. Hanna, Henry E. Kane, R. J. LeBlanc, and E. McFarlan, Jr. Initial planning of the trip was assisted by M. A. Hanna, H. N. Fisk, and T. D. Cook. All members of the field trip committee served as commentators in the field and contributed material used in preparation of the excellent guidebook. Several others also assisted in the field and presented papers for the preceding symposium. Approximately 100 attended this field trip. Guidebooks for this trip and the one discussed above can be obtained through the Houston Geological Society.

11. *Report of the Pacific Coast Section (Weldon W. Rau).*—The Pacific Section has an active paid-up membership of 161, and a balance in the treasury of $1,765.51. President of the Section is Weldon W. Rau and secretary-treasurer is Richard L. Brooks.

This year, National and Pacific Section S.E.P.M. membership awards and subscriptions to both journals were granted to sixteen students from various Pacific Coast colleges and universities. The faculty of the paleontology or geology department of each school nominated the student to receive the award.

The monthly Biostratigraphy Seminar, sponsored jointly by the Pacific Section S.E.P.M. and the Bakersfield College is in progress. Eight papers by distinguished research workers from the West Coast, covering the field of stratigraphy, paleontology, and ecology are being presented. Mr. Richard Pierce is chairman, and the average attendance at the meetings is approximately fifty.

The S.E.P.M. Pacific Section will sponsor their annual dinner meeting and field trip on April 15 and 16. Dr. Alfred Loeblich is chairman of the event. The geology and paleontology of rocks of Cretaceous age will be studied in the vicinity of the Panoche Hills, California. The Friday evening dinner meeting will be held at the Hacienda in Fresno, California. Mr. Max Payne will present a paper on the stratigraphy of the Panoche Hills. He will also lead the field trip on the following day.

The Pacific Section S.E.P.M. will again cooperate with the A.A.P.G. and S.E.G. in putting on the thirty-seventh annual fall meeting at Los Angeles on November 3 and 4. A two-day technical session and dinner meeting are being planned by Dr. Alfred Loeblich, program chairman.

A dinner dance will be held in December which is co-sponsored by the S.E.P.M., A.A.P.G., and S.E.G.

12. *Report of the S.E.P.M. Delegate to the IX International Botanical Congress Montreal, Quebec, August, 1959 (Alfred Traverse).*—Largely because of the interest of economic micropaleontologists in fossil plant nomenclature—especially that of fossil pollen and spores—S.E.P.M. appointed a delegate to the IX International Botanical Congress, held in Montreal in August of 1959. Mostly as a result of the mushrooming volume of publication on fossil pollen and spores interest in paleobotanical nomenclature and its position in the International Code of Botanical Nomenclature ran relatively high prior to and during the Montreal congress.

About fifty proposals to amend paleobotanical provisions of the Code were published by paleobotanists (including paleopalynologists) before the Congress. These were rather fully discussed, both in print and at several symposia on nomenclature, in the years between the Paris VIII International Botanical Congress (1954) and the Montreal meeting. The proposals ranged from radical ones tending toward creation of a separate code for fossil pollen and spores, to conservative ones aimed at eliminating obvious errors of language in the Code adopted at Paris in 1954.

The results of the deliberations of the Committee for Paleobotanical Nomenclature at Montreal were accepted nearly *in toto* by the Bureau of Nomenclature, and by the Congress as a whole. These results were fundamentally conservative. Not only were proposals to create special status for fossil pollen and spores rejected, but even the existing separate paleobotanical appendix in the Paris 1954 and earlier codes was eliminated. In the Code adopted at Montreal it is, therefore, emphasized that fossil pollen and spores are amenable to the same sort of nomenclatural treatment as are other categories of plant fossils and are not to be thought of as being slightly beyond the pale. Furthermore, the abolition of the erstwhile paleobotanical appendix, as well as adoption of several specific emendations of the rules, emphasized that all specimens of fossil plants are to be handled as representating taxa of plants. Several emendations were directly aimed at eliminating any possible doubt about this.

It is the opinion of the S.E.P.M. delegate to this meeting that the decisions made at Montreal were most salutary in making it plain that nomenclature of fossil pollen and spores is governed by the botanical rules, based on typification and priority, wherever formal names are used. Any tendency toward anarchy that may have existed has been reversed. This does not mean that fossil pollen must have formal names, of course; classification by symbols or informal terms is often preferable, though it has no formal status.

13. *SEPM President's Report (Samuel P. Ellison, Jr.)*—Based on the Secretary-Treasurer's report, the financial condition of the Society remains good in the face of rising printing and operating costs. Increased printing costs of the two journals and increases in expenses account for the decline of the General Fund but all of the special publications are now operating at a profit except the *Journal of Sedimentary Petrology* Index. The splendid sale of the special publications accounts for the improvement in the status of the Publications Fund.

Our very energetic membership committee under the chairmanship of John P. Brand has brought a total of 153 new members and associates into the Society. After drops due to non-payment of dues, the Society had a total net gain of 74 (5% gain) in 1959 as compared to a gain of 43 in 1958. I recommend the continuation of an active membership committee to not only increase the new memberships but also to encourage members in arrears to stay active.

The research committee under the chairmanship of Arthur C. Munyan organized a symposium on "Paleontological and Mineralogical Aspects of Polar Wandering and Continental Drift" for presentation at Atlantic City. The committee also selected the recipients of honorary membership and best paper awards for the journals. The committee under the chairmanship of Robert Ginsburg are planning a symposium on

"Oceanography" for the Denver meeting next year.

The editors of our journals reported increased pages for both journals and an increased back-log of unpublished manuscripts on hand. A wide variety of papers from many national origins was published in both journals. A pressing need still exists for further expansion of our volumes. However, the council by necessity has adopted a 1960–61 budget that does not permit expansion of the journals.

The Council has approved the reprinting of the special publication "Regional Aspects of Carbonate Deposition." The Barker manuscript on the revision of the "Foraminifera of the Challenger Expedition" complete with plates is expected to be off the press in the summer of 1960. An Index to the Journal of Paleontology is also in press as a special publication.

The membership voted overwhelmingly to change the bylaws so that by April, 1961, the Council will be increased by two councilors. This was to increase the pool of members eligible for the presidency. The membership also advised the Council by a referendum vote that it desired to maintain the two slate method of election of officers.

The activities of the three organized sections, Gulf Coast Section, Permian Basin Section, and Pacific Section are on the increase. Field trips, regional meetings, student awards, and publications are on the programs of each section. I had the pleasure of visiting the meetings of two of the sections during the past year and I was impressed with the vigorous activity.

At its meeting of April 24, 1960, the Council of the Society gave careful consideration to the American Geological Institute reorganization proposals. The Council passed unanimously a resolution supporting these proposals in principle. Decision to raise the Society's dues for support of the American Geological Institute will, of course be made by a vote of the membership at large.

I wish to extend my sincerest gratitude to the many members of the Society who have served as officers, editors, representatives, committee chairmen and committee members during my term of office. Further, our Society is deeply indebted to the capable work performed by the Tulsa headquarters staff.

After the president's report, the meeting was turned over to the Incoming President, William M. Furnish, who called on Carl C. Branson to present the "Resolutions of Thanks."

The Resolutions Committee, composed of Carl C. Branson (Chairman), Bernhard Kummel, and E. C. Dapples, presents the following "Resolutions of Thanks."

"BE IT RESOLVED THAT in behalf of the Society, we extend an expression of our sincere thanks to the following:

TO WILLIAM J. PLUMLEY, technical program chairman, for the assembling of and the efficient handling of the technical program;

TO RICHARD S. BOARDMAN, S.E.P.M. vice-chairman, for his capable management of the many details involved in having a successful convention;

TO ARTHUR C. MUNYAN, chairman of the Research Committee, for securing papers and preparing the Research Symposium, "The Paleontological and Mineralogical Evidence for Polar Wandering and Continental Drift";

TO PAUL TASCH and ALBERT L. KIDWELL for arranging the program on paleontology and mineralogy;

TO HARRY S. LADD, general chairman, GEORGE V. COHEE, general vice-chairman, FRANCIS J. PETTIJOHN, A.A.P.G. program chairman, and to the chairmen and members of all the convention committees for their efforts in behalf of the meeting;

TO THE EXECUTIVE COMMITTEE of the A.A.P.G. for appropriating $2,000.00 as office rent for the Society Headquarters at Tulsa;

TO OUR EDITORS, M. L. THOMPSON, CHARLES W. COLLINSON, and JACK L. HOUGH for maintaining the high quality of our Journals;

TO ROBERT H. DOTT for his sound and discerning judgment in the business affairs of our Society;

AND TO THE CHALFONTE-HADDON HALL for providing excellent convention headquarters facilities."

It was moved, seconded, and carried that the meeting be adjourned.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 30, NO. 2, PP. 342–346
JUNE, 1960

CONSTITUTION AND BY-LAWS

(AMENDED, 1959)

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

A DIVISION OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

CONSTITUTION

ARTICLE I. NAME

The Society shall be known as the Society of Economic Paleontologists and Mineralogists.

ARTICLE II. OBJECT

The object of the Society shall be to promote the science of stratigraphy through research in paleontology and sedimentary petrology, especially as these relate to development of knowledge of the geology of petroleum.

ARTICLE III. MEMBERSHIP

1. The Society shall be composed of active members, associate members, honorary members, correspondents, and patrons.

2. Active members shall be persons engaged in paleontologic, petrographic, or stratigraphic studies as applied to the geology of petroleum and who have been duly elected active members, juniors, or associates in The American Association of Petroleum Geologists.

Active and honorary members only shall be known as members.

3. Associate members shall be known as associates. Any person engaged in paleontologic, petrologic, or stratigraphic studies that have application to the geology of petroleum is eligible for associate membership. Associates shall enjoy all the privileges of membership in the Society, save that they shall not hold office, sign applications for membership, or vote.

4. Honorary members shall be persons of distinguished achievement whose contributions to paleontology, petrology, and stratigraphy have an application to the geology of petroleum.

5. Correspondents shall be persons not resident in North America who have made distinctive contributions to paleontology, petrology, and stratigraphy that have application to the geology of petroleum.

6. Patrons shall be persons who have bestowed important favors on the Society.

ARTICLE IV. OFFICERS

1. Executive authority of the Society is vested in a council consisting of eight members, duly elected officers, as follows: president, vice-president, secretary-treasurer, the past-president, two councilors, and the editor of each of the two Journals. The chairman and the vice-chairman of the Research Committee and the presidents of Regional Sections shall be non-voting members of the council.

2. The president shall discharge the usual duties of a presiding officer at all meetings of the Society and council.

3. The vice-president shall assume the duties of the president in case of his absence.

In the event of the absence from the meetings of both president and vice-president, the duties of presiding officer shall fall upon one of the other members of the council in the following order: past-president, secretary-treasurer.

4. The secretary-treasurer shall keep records of the proceedings of the Society, and a complete list of the membership. He shall attend to the preparation and mailing of notices and other materials required in the business of the Society. The secretary-treasurer shall have custody of all funds of the Society, and shall keep a detailed account of receipts and disbursements.

5. The councilors shall participate in the deliberations of the council and perform specific duties with respect to membership, publications, and other affairs of the Society as shall be assigned to each by the president.

6. The council shall consider all nominations for membership and pass on the qualifications of the applicants; may elect honorary members, correspondents, and patrons; shall have control and management of the affairs and funds of the Society; shall determine the manner of publication and pass on the material presented for publication; and

shall designate the place of the annual meeting. In the event of a tie vote among the voting council, the president, vice-president, and secretary-treasurer's votes shall prevail. The council is empowered to establish a business headquarters for the Society and to employ such persons as are needed to conduct the business of the Society.

7. Elections shall be held annually to select a president, vice-president, secretary-treasurer, two councilors, and the editors.

ARTICLE V. MEETINGS

1. The Society shall hold at least one stated meeting a year, which shall be designated as the annual meeting. The time and place of the annual meeting shall be designated by the council, but in general, it shall be held in connection with the annual meeting of The American Association of Petroleum Geologists.

2. The annual meeting shall be devoted to the reading and discussion of scientific papers, to the transaction of Society business, and other appropriate functions.

3. The program for the annual meeting shall be arranged by the council, or under its direction.

ARTICLE VI. SECTIONS

Local sections of the Society may be established according to provisions of the by-laws.

ARTICLE VII. AMENDMENTS

The constitution may be amended by a two-thirds vote of returned mail ballots received by the secretary-treasurer sixty days after proposal of amendments with provision for vote is mailed to the membership; provided that the proposed amendment has been signed by at least twenty members, and provided further that the proposed amendment must first have the approval of the council and the executive committee of The American Association of Petroleum Geologists.

BY-LAWS

ARTICLE I. DUES

1. The fiscal year of the Society shall correspond with the calendar year.

2. The annual dues of members and associates of the Society who desire only the *Journal of Paleontology* shall be ten dollars ($10.00). The annual dues of members and associates who desire only the *Journal of Sedimentary Petrology* shall be seven dollars ($7.00). Members and associates may receive both Journals by the payment of seventeen dollars ($17.00). Members of the Society who are also members of the Paleontological Society and receive the *Journal of Paleontology* through the latter Society, may retain membership in the Society of Economic Paleontologists and Mineralogists by the payment of two dollars ($2.00) per year dues. The annual dues are payable in advance on the first day of each calendar year. A bill shall be mailed to each member and associate before September 1 of each year, stating the amount of annual dues and the penalty and conditions for default of payment. Members and associates who shall fail to pay their annual dues by January 1 shall not receive further copies of either Journal, nor shall they be privileged to buy Society publications at special discounts made to the membership, until such arrears are met.

3. The council may from time to time elect as honorary members, correspondents, and patrons, candidates who have been nominated by a majority vote of the research committee. A vote of four members of the council shall be required for election. Honorary members, correspondents, and patrons shall not be required to pay annual dues.

ARTICLE II. DUTIES AND PRIVILEGES OF MEMBERS

1. Members and associate members dropped for non-payment of dues may apply to the council for reinstatement, and, provided settlement is made of any outstanding indebtedness for publications and other charges approved by the council, may be reinstated by vote of four members of the council.

2. Members shall be eligible to receive publications of the Society at special subscription rates as authorized by the council or as provided in these by-laws.

3. The council is authorized to transmit without charge such publications as it may direct to honorary members, correspondents, and patrons.

4. Only active and honorary members shall have the right to vote in electing officers and in transacting the business of the Society.

ARTICLE III. OFFICERS

1. Nominations for officers shall be made in the following manner. Prior to September 1 of each year, the president shall designate a nominating committee to consist of not less than five members, none of whom shall be members of the council, instructing this committee to submit two nominations for president, vice-president, and secretary-treasurer, four nominations for the offices of councilor, and nominations for editors of the two Journals, these nominations to be in the secretary's hands before September 15. If desired, this committee may nominate two slates of candidates for editor of one or both of the Journals.

2. Ballots containing the nominations for officers, alphabetically arranged under each office, shall be prepared by the secretary-treasurer and mailed to each member of the Society on or before October 1. Neither the ballot nor the enclosing envelope need contain the name of the voting member, but an outer envelope that contains the sealed ballot must bear the name of the voting member. The returned ballots received by the secretary-treasurer on or before December 1 shall be counted by him, and if requested, shall be submitted to recount by the council. A plurality of the votes received for any office constitutes election.

3. If, after his election by the regular ballot, the president shall not be able to discharge the duties of his office, because of death or resignation, the duly elected vice-president shall then assume the duties and title of president with all of the authority vested in him by the Constitution. In the event the vice-president shall not be able to assume said duties, then the succession shall be in the following order: past-president, secretary-treasurer. If none of the above mentioned members of the council shall be able to assume the office of the president, then a special election shall be held in which at least two qualified members, nominated by the council, shall be voted upon by the membership by means of a special mailed ballot. Any vacancies in the normally constituted council caused by such succession or for any other reason may be filled with a temporary appointment by the council.

4. Nominees for the office of president shall be active members in good standing who shall have served, or may be serving concurrently at the time of nomination, as vice-president, secretary-treasurer, councilor, chairman of the Research Committee, or editor of one of the Society's official publications.

5. The vice-president shall be the officer of the council responsible for arrangements for the annual meeting, including selection of program chairmen, and shall keep in close contact with the Research Committee and others concerning technical papers and symposia to be presented.

ARTICLE IV. PUBLICATIONS

1. There shall be two editors, one for the *Journal of Paleontology* and one for the *Journal of Sedimentary Petrology*. The editors shall be in charge of editorial business of their respective Journals. Each shall submit an annual report of such business, shall have authority to solicit papers and material for such Journals, and may appoint associate or co-editors.

2. The *Journal of Paleontology* and the *Journal of Sedimentary Petrology* are designated as official publications of the Society. The council is not authorized to initiate and publish other periodicals.

3. A publication fund may be established consisting of an assignment of a portion of dues as designated by the council, and such donations as are specifically made for that purpose. The council is authorized to provide special publications from this fund as may be deemed desirable, and to fix terms for sale or other distribution of these publications.

ARTICLE V. FINANCIAL METHODS

1. No financial obligations shall be contracted without express sanction of the Society or council, but all ordinary incidental running expenses have sanction without special action.

2. Statements of accounts charged to the Society, other than miscellaneous running expenses, shall be approved by the president before the secretary-treasurer pays the

amount out of funds of the Society not otherwise appropriated, and the receipted bill shall be held as the secretary-treasurer's voucher.

3. The secretary-treasurer shall have charge of the financial affairs of the Society and shall annually submit reports as secretary-treasurer covering the fiscal year. He shall receive all funds of the Society, and, under the direction of the council, shall disburse all funds of the Society. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded all employees to whom authority may be delegated to handle Society funds. The amounts of such bonds shall be set by the council and the expense shall be borne by the Society. The funds of the Society shall be disbursed by check as authorized by the council.

ARTICLE VI. BUSINESS REPRESENTATIVES

The president and the secretary-treasurer of the Society shall act as business representatives of the Society in the business committee of The American Association of Petroleum Geologists. These representatives shall conduct such business with the executive committee of the Association as is of mutual interest to the Society and the Association in the interims between the annual meetings of the Society and the Association. Approval of the action of these representatives on the part of the Society during any year is reserved to the council in session at the annual meeting at the close of that year. Questions remaining unsettled between the representatives of the Society and the executive committee of the Association shall be considered in a joint meeting of the council of the Society or its authorized representatives and the executive committee of the Association at the annual meeting of the Association at the close of the interim period during which such questions have arisen.

ARTICLE VII. SECTIONS

1. The establishment of local sections of the Society may be authorized by unanimous vote of the council approving a petition for such establishment signed by ten members of the Society. Such local sections may elect officers, conduct meetings, and engage in other scientific activities.

2. The council is authorized and directed to withdraw the charter of any established local section if there is evidence that it has become inactive.

ARTICLE VIII. DIRECTORS OF AMERICAN GEOLOGICAL INSTITUTE

1. The president and the past-president shall be directors of the American Geological Institute, the past-president being the senior director. They shall represent the Society on said Institute. The term of office as directors shall begin at the fall meeting of the American Geological Institute following assumption of their office and shall terminate two years later; provided that this provision in no way extends their terms of office as members of the council of the Society.

2. In the event of a vacancy by resignation, death, or other causes among the two directors who represent the Society on said Institute, the president of the Society shall nominate a director from the ranks of active members of the Society, and this director shall complete the unexpired term.

ARTICLE IX. REPRESENTATIVE ON NATIONAL RESEARCH COUNCIL

At the expiration of each three-year term, the president shall appoint a representative on the National Research Council to serve for a term of three years.

ARTICLE X. RESEARCH COMMITTEE

1. The objectives and duties of the Research Committee shall be to foster and encourage research; to advise the Society and council on research activities which may concern the Society, or which may be recommended or initiated under its sponsorship; to develop a symposium for the annual meeting if so requested; to select recipients for Best Paper Awards each year for each Journal; to nominate candidates for honorary members, correspondents, and patrons; and to deal with any other matters referred to it from time to time by the president or the council.

2. The activities of the Committee shall be directed by a chairman and a vice-chairman, to be appointed by the president, with

the approval of the council, from the active members of the Committee. The term of the appointment of the chairman shall be one year. The vice-chairman will normally succeed the chairman the following year. In the event either of these offices is vacated for any reason, the council shall appoint a qualified replacement for the unexpired term.

3. Membership of the Committee shall be appointed by the president from members and associates of the Society. The Committee shall consist of fourteen members, but this total may be changed at the discretion of the council. Two committee members, preferably one paleontologist and one mineralogist, shall be chosen from each of several geographic regions to be selected by the council. In addition, advisory members may be appointed from foreign areas. The terms of appointment of members and advisory members shall be for three years. Appointments shall be staggered, with the junior member from any region serving at least one year with the senior member from that region. If vacancies develop on the Committee the president shall make suitable appointments for the unexpired term.

ARTICLE XI. PUBLICATIONS COMMITTEE

1. The membership of this committee shall consist of five members, including a chairman, three other members, and the chairman of the Research Committee as an ex-officio member. The tenure of office of the chairman and members shall be two years. Membership of the committee shall be appointed by the president from members and associates of the Society.

2. The duties of the Publications Committee shall be to recommend to the council manuscripts or symposia which merit consideration as S.E.P.M. special publications. The Publications Committee shall further recommend type of reproduction, number of copies, and cost figures of manuscripts or symposia.

3. Upon approval of the council, this committee, with the appropriate Society editor or editors, shall edit (or have edited), and publish these manuscripts or symposia.

4. The activities of this committee will include recommending to the council suggestions for improving the quality of our Society *Journals* consistent with the budgeted monies allotted for publication.

ARTICLE XII. AMENDMENTS

The by-laws may be amended at any annual business meeting by two-thirds vote of the members present, or by mail ballot sent to the members, in which case two-thirds of the returned ballots received in sixty days after mailing must approve the amendment in order to make it effective. Any proposed changes to the by-laws must first have the approval of the council.

Mineralogy: Concepts, Descriptions, Determinations, by L. G. Berry and Brian Mason, 1959. Pp. xi+612, 265 figs.; 6×9 in., cloth. W. H. Freeman and Company, San Francisco. Price $8.75.

Dana's Manual of Mineralogy, 17th ed., by C. S. Hurlbut, Jr., 1959. Pp. xii+609, 634 figs., 6×9 in., cloth. John Wiley & Sons, New York. Price $11.50, textbook ed., $9.50.

The two books under review are of more than ordinary interest because they reflect some of the changes being made in the teaching of mineralogy. The first listed book is new, the second is new in much of its content and approach. Both are intended as texts for undergraduate courses in mineralogy.

The two principal features of the two include: improved (compared to previous texts) comprehensiveness and rigour of treatment of crystallography (including stereographic projection and calculations); survey of the essential principles of crystal chemistry; emphasis upon crystal structural features of minerals (with abundant well chosen and executed illustrations); atomistic explanations of many mineral properties; added emphasis upon solid solution and its consequences; consideration of phase relations (using phase diagrams) in geologic systems; up-to-date data for the 200 or so minerals treated in each book; and useful references for further reading. Of interest to sedimentary petrographers are the relatively detailed descriptions of the nature of the clay and carbonate minerals. Both books present only brief descriptions of chemical testing (approximately one-third the length alloted in previous books).

Although similar in these respects, the books differ in level, method, and detailed content. Berry and Mason presume the reader to be familiar with plane trigonometry and to have a good knowledge of modern chemistry. They present more developmental, and slightly more detailed and sophisticated explanations than does Hurlbut. The latter is more descriptive and is characteristically lucid, cleanly organized and to the point. I would judge the new "Manual" to be a good introductory text for students having little or no background in mathematics and the physical sciences and Berry and Mason's text to be more suitable for those with a better background. The latter book should also be of value to practicing geologists who wish to up-date their knowledge of mineralogy.

The principal differences in treatment are that Berry and Mason start with and consider elementary pattern theory (lattices and point groups), make use of gnomonic projections and more use of crystallographic calculation, give more atomistic explanations of mineral properties, utilize a simple geochemical approach in considering the occurrences of minerals, make more use of the concept of phases and of phase diagrams, and give a few more diagrams showing solid solution limits and the variation of properties with composition. Hurlbut, on the other hand, begins with a consideration of crystals from an external point of view and emphasizes those features that students can easily and immediately observe themselves. He presents also a concise but inclusive description of x-ray crystallography, a subject scarcely more than mentioned by Berry and Mason.

Both books are welcome additions and should help to remedy the long-standing lack of adequate mineralogy texts.

D. M. HENDERSON
University of Illinois

Structural Methods for the Exploration Geologist by Peter C. Badgley, 1959. Pp. xv +281, 329 figures, 10 plates, 8½×11 in., cloth. Harper's Geoscience Series, Carey Croneis Editor, Harper and Brothers, New York. Price $7.50.

The publication of problems for structural geology students has been considered usually as a minor field and indeed never attracted the attention it deserved as the indispensable complement to textbooks mostly devoted to theoretical aspects. The few available books on structural methods deal mostly with abstract cases and offer a difficult problem of integration with the usual textbooks. Moreover, numerous useful tables and data remain scattered in many other publications.

Most of these shortcomings have been met by Dr. P. C. Badgley's *Structural Methods for the Exploration Geologist* which will certainly receive a hearty welcome from instructors in structural geology. It is a comprehensive work displaying problems which range from simple determinations of dip and strike by the three points method to complex situations such as the tectonic analysis of entire exploration provinces.

Practically every modern method used in solving structural problems is related to fundamental principles, theoretically discussed in details with a minimum of mathematics and a maximum of diagrams, and finally illustrated by actual field problems. These case histories represent one of the most interesting and stimulating aspects of the book.

The author should also be congratulated for two features of his presentation. The first one consists of the demonstration of the importance of selecting the most suitable method of analysis and interpretation for a given structural situation. The second one is the accent put on the wide range of possible structural interpretations of a given case.

Worthy of particular mention is the continuous emphasis on three-dimensional thinking without which structural geology cannot be fully understood, and I may say cannot be understood at all. The numerous students who have difficulty in appreciating spatial relations will find in Dr. Badgley's book a very welcome help.

Each chapter ends with a rather comprehensive list of references. Such a complete bibliographical treatment of the entire range of structural methods currently in use followed by a set of sixteen mosaic and overlapping air photographs shows how different this book is from the usual collections of structural problems. It is in fact a laboratory or field manual on geological structures and an ideal complement to advanced textbooks such as L. U. de Sitter's "Structural Geology."

The reviewer would have liked, however, a more international approach to the question particularly with regard to the expanding overseas exploration; for instance, by including some of the classical European case histories such as the well-documented experiences of the Hauenstein, Grenchenberg and Weissenstein tunnels which revealed the disharmonic folds of the Jura Mountains. Very helpful also would have been a discussion of some of the problems presented by the construction of structure contour maps and cross-sections in complex overthrusts and recumbent folds of the Alps, exemplified for instance by the classical case of the Simplon tunnel.

But these are only minor criticisms of the book which merits great praise and which represents an indispensable addition to the library of any professional geologist whichever his specific field happens to be.

ALBERT V. CAROZZI
University of Illinois

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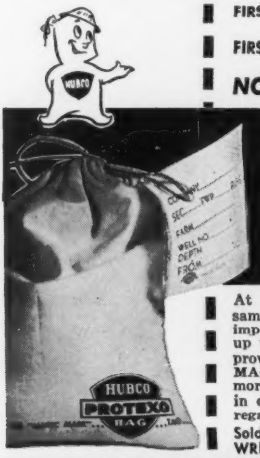

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